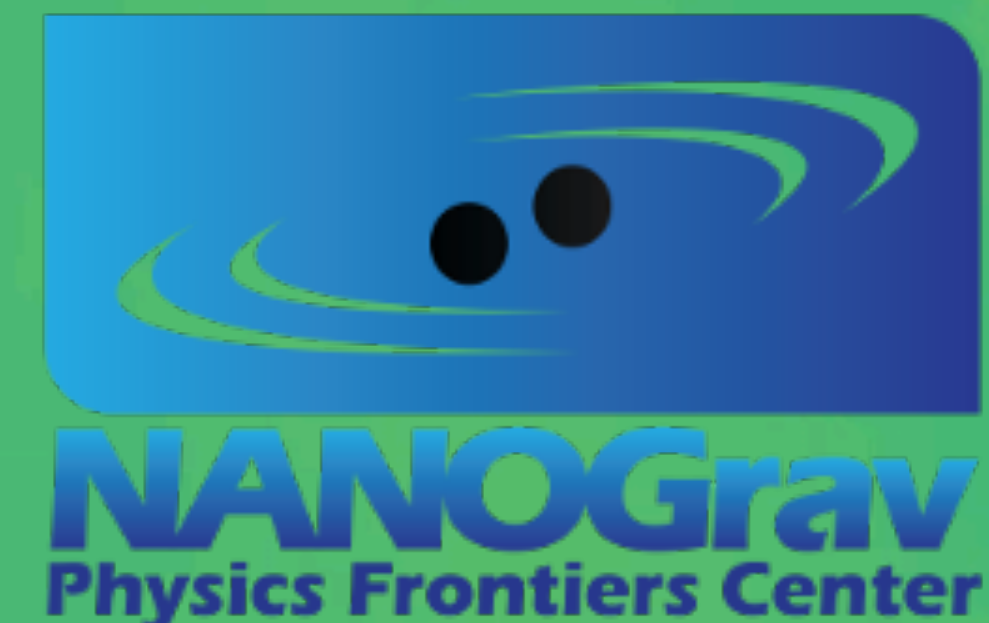
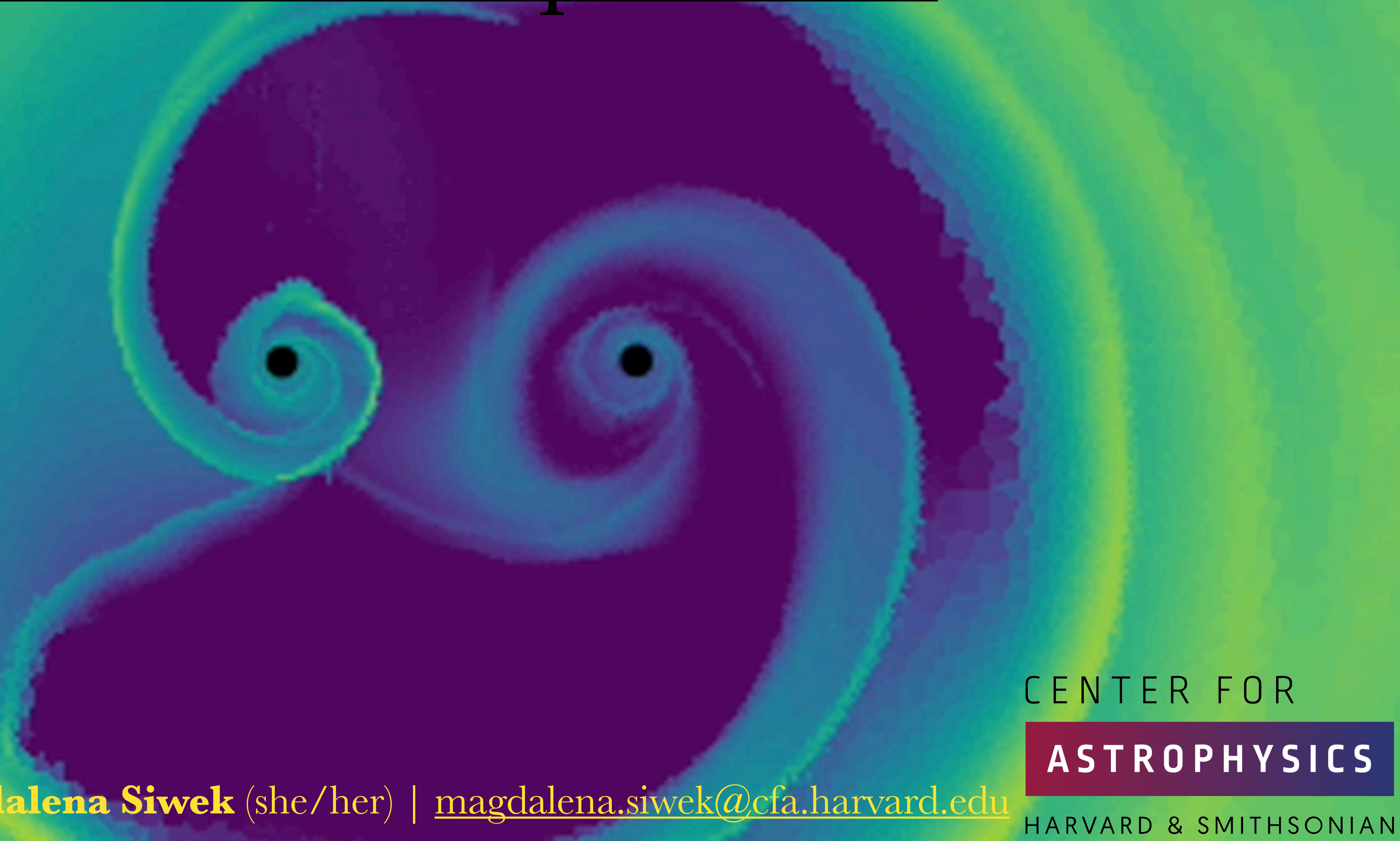


# Signatures of Circumbinary Disk Physics in MBHB Populations



**Magdalena Siwek** (she/her) | [magdalena.siwek@cfa.harvard.edu](mailto:magdalena.siwek@cfa.harvard.edu)

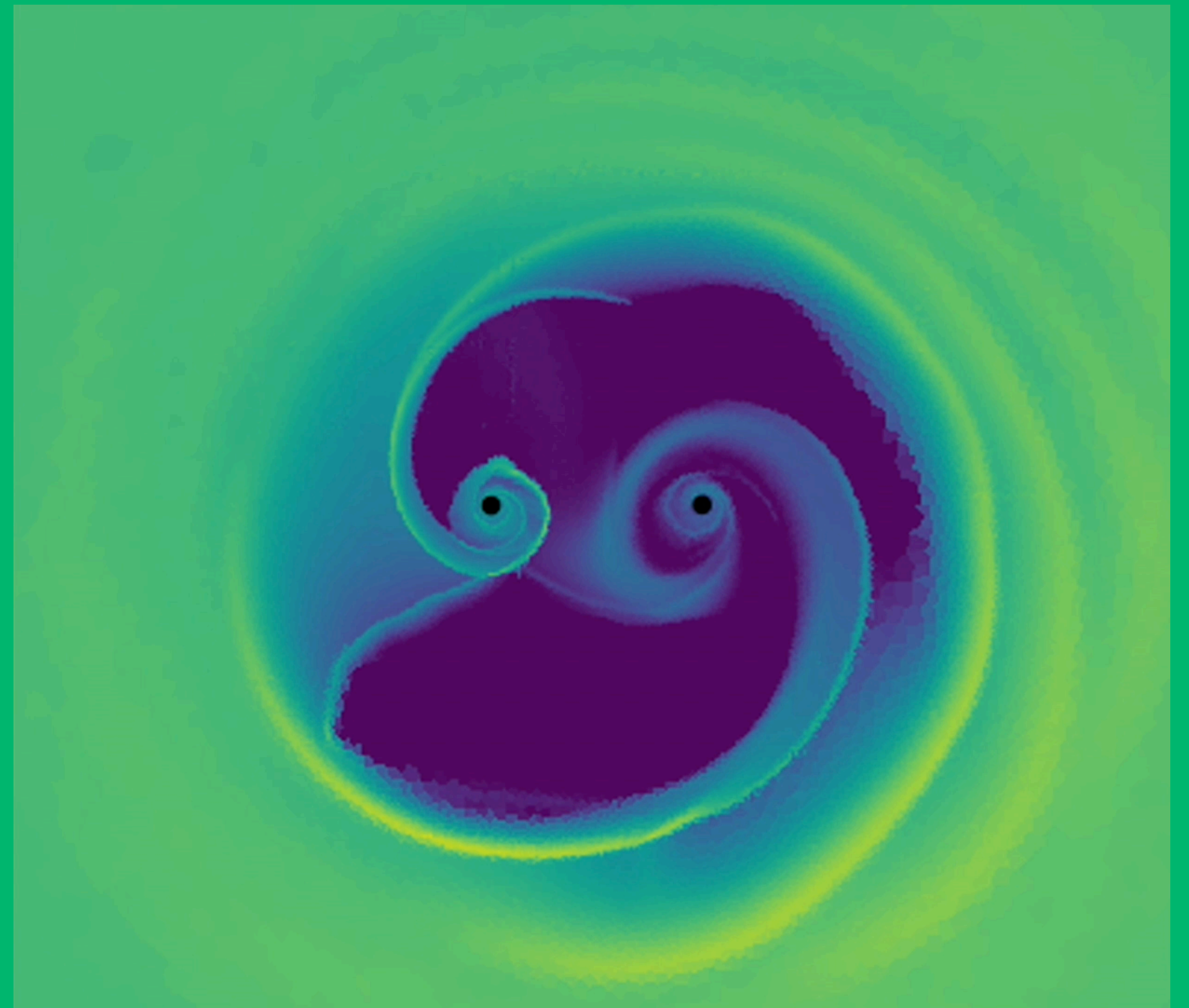
CENTER FOR

**ASTROPHYSICS**

HARVARD & SMITHSONIAN

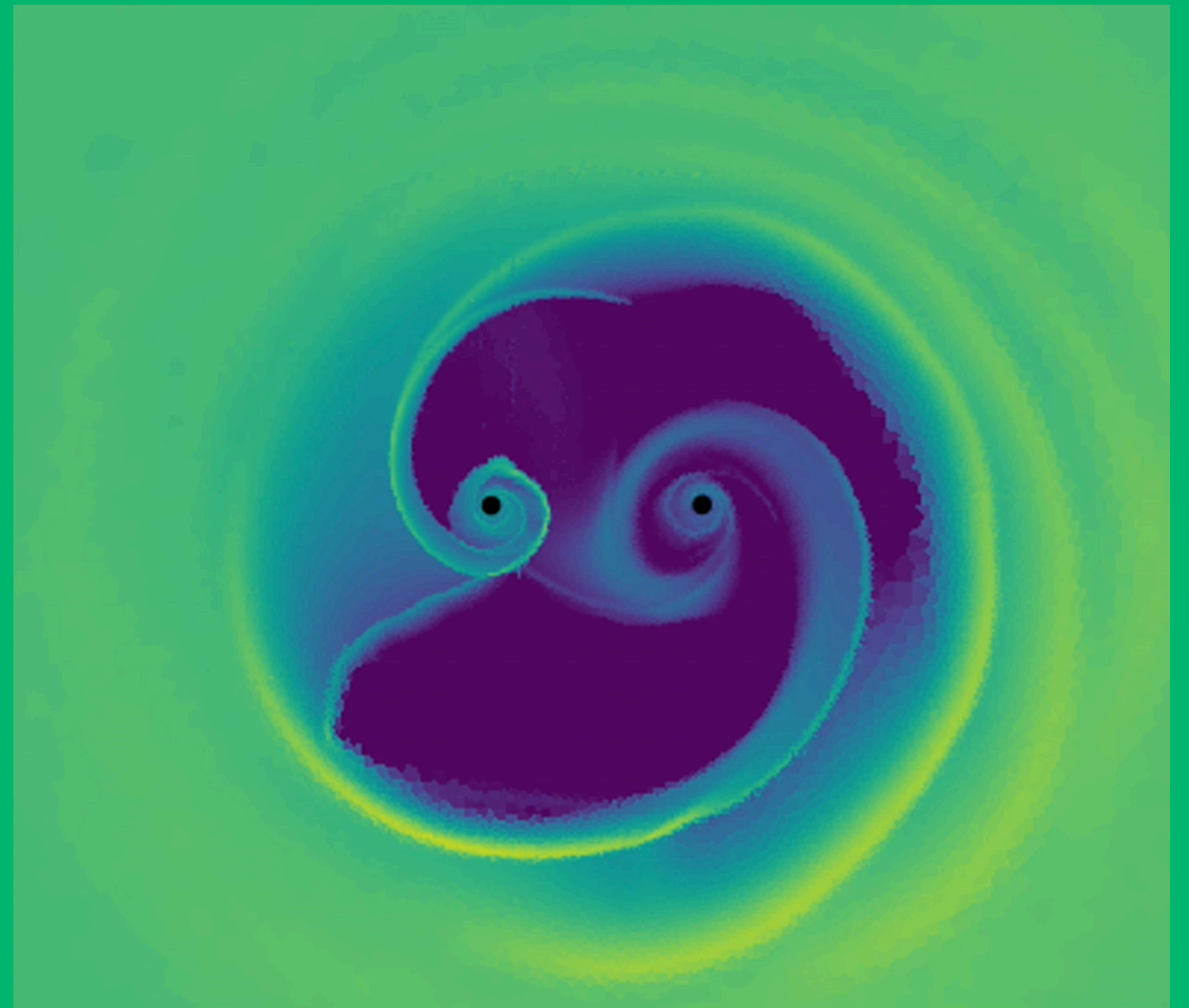
# Signatures of Circumbinary Disk Physics in MBHB Populations

1. MBHBs: Formation & Evolution
2. Circumbinary Disk (CBD) Simulations
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4. Electromagnetic Signatures & CBD accretion variability



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# The Formation of Massive Black Hole Binaries



Post Galaxy Merger



$\text{kpc} \gtrsim a_b \gtrsim 1 \text{ pc}$

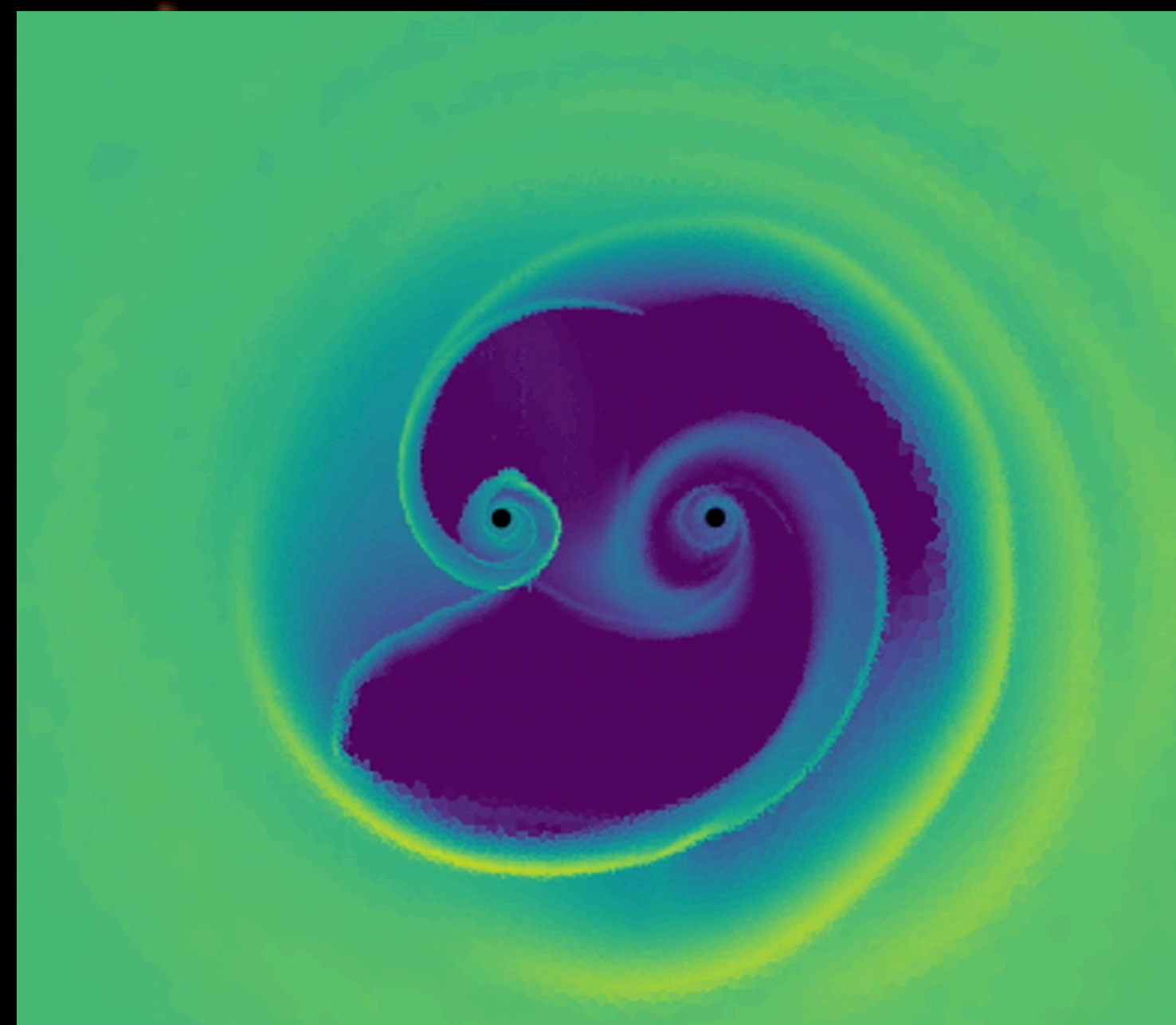
Dynamical  
Friction

+

Stellar  
Scattering



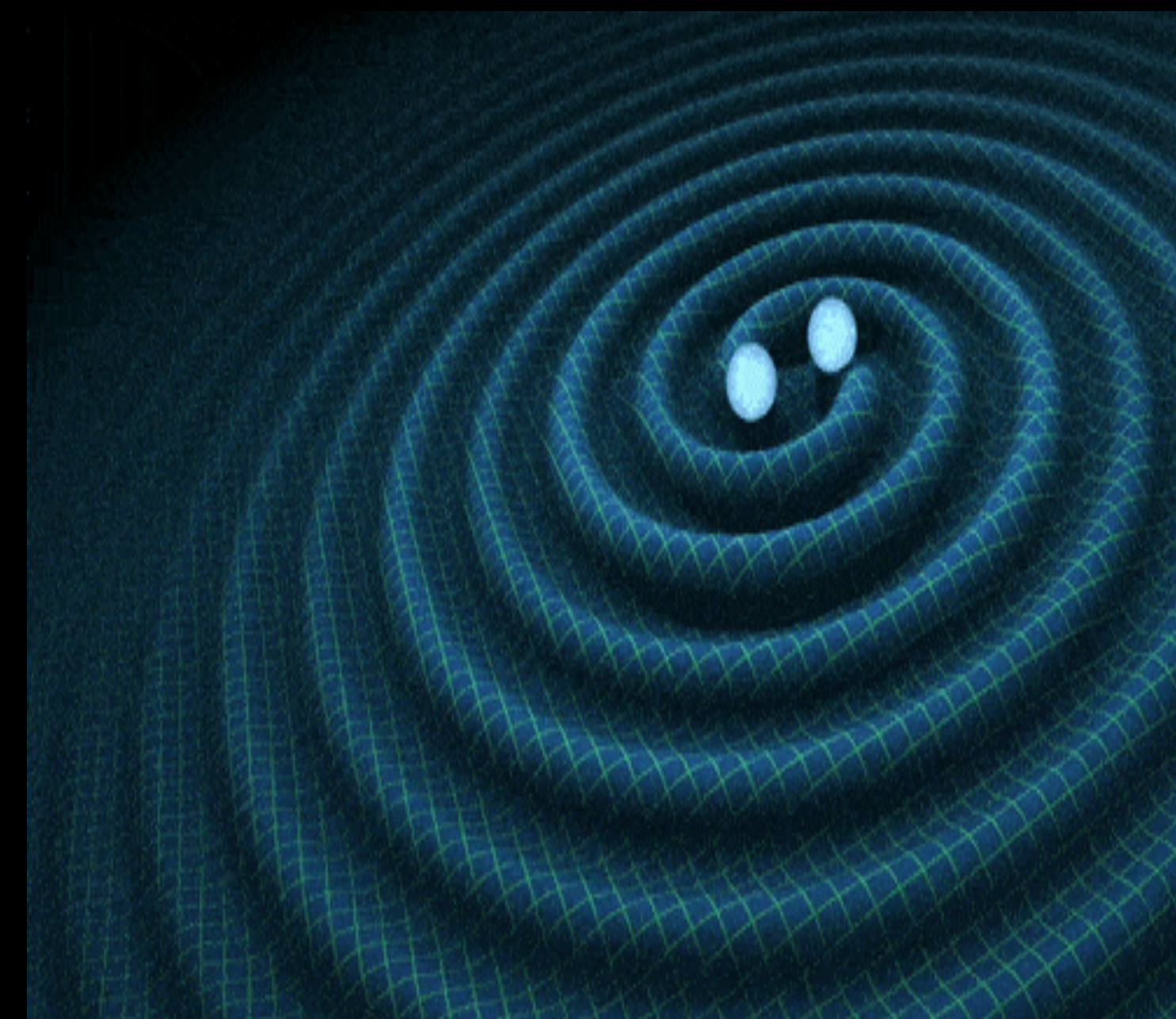
CBD-driven phase



$1 \text{ pc} \gtrsim a_b \gtrsim 10^{-2} \text{ pc}$



GW emission



$a_b \lesssim 10^{-2} \text{ pc}$

# Post Galaxy Merger



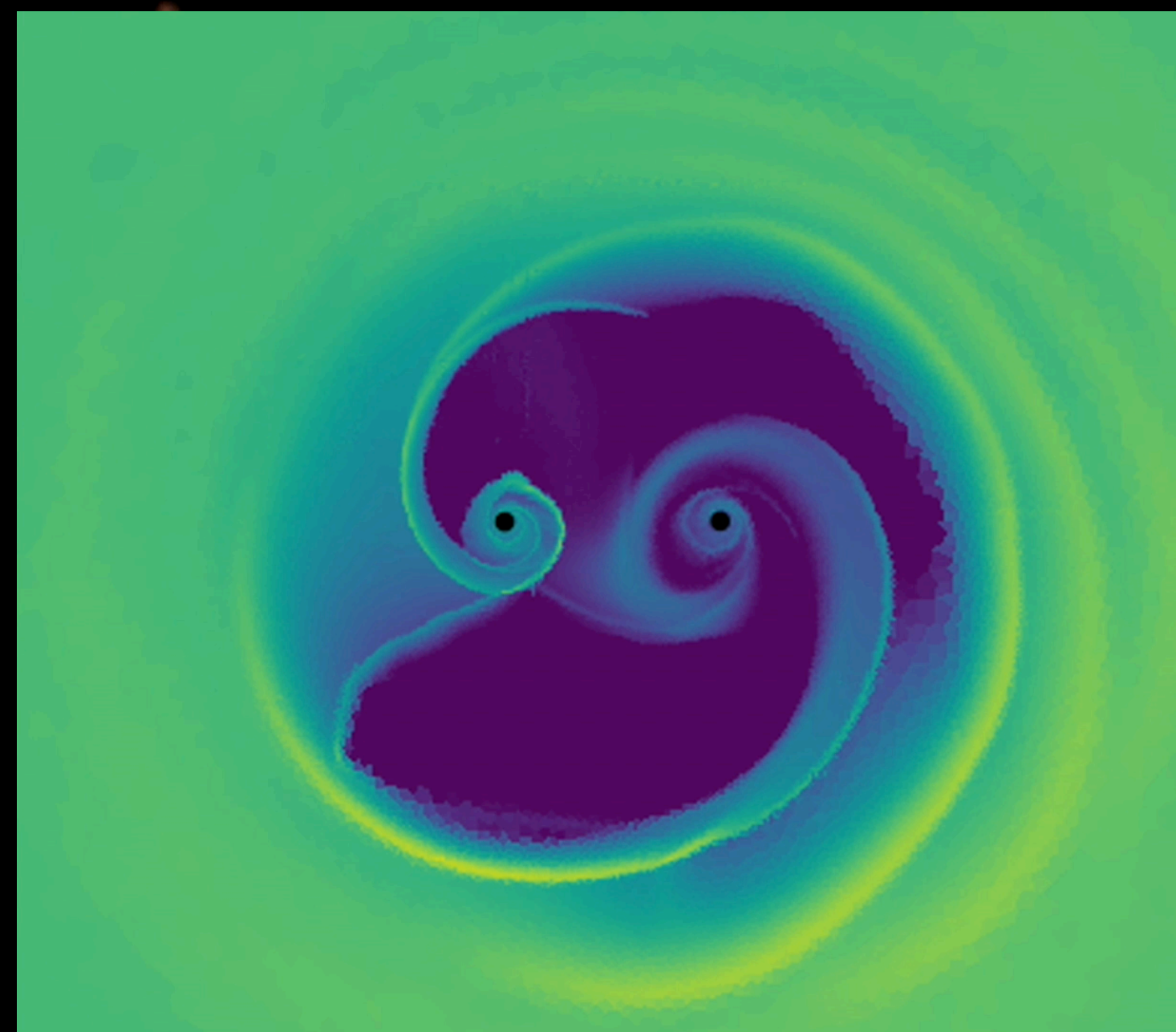
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Dynamical Friction

+

Stellar Scattering

# CBD-driven phase

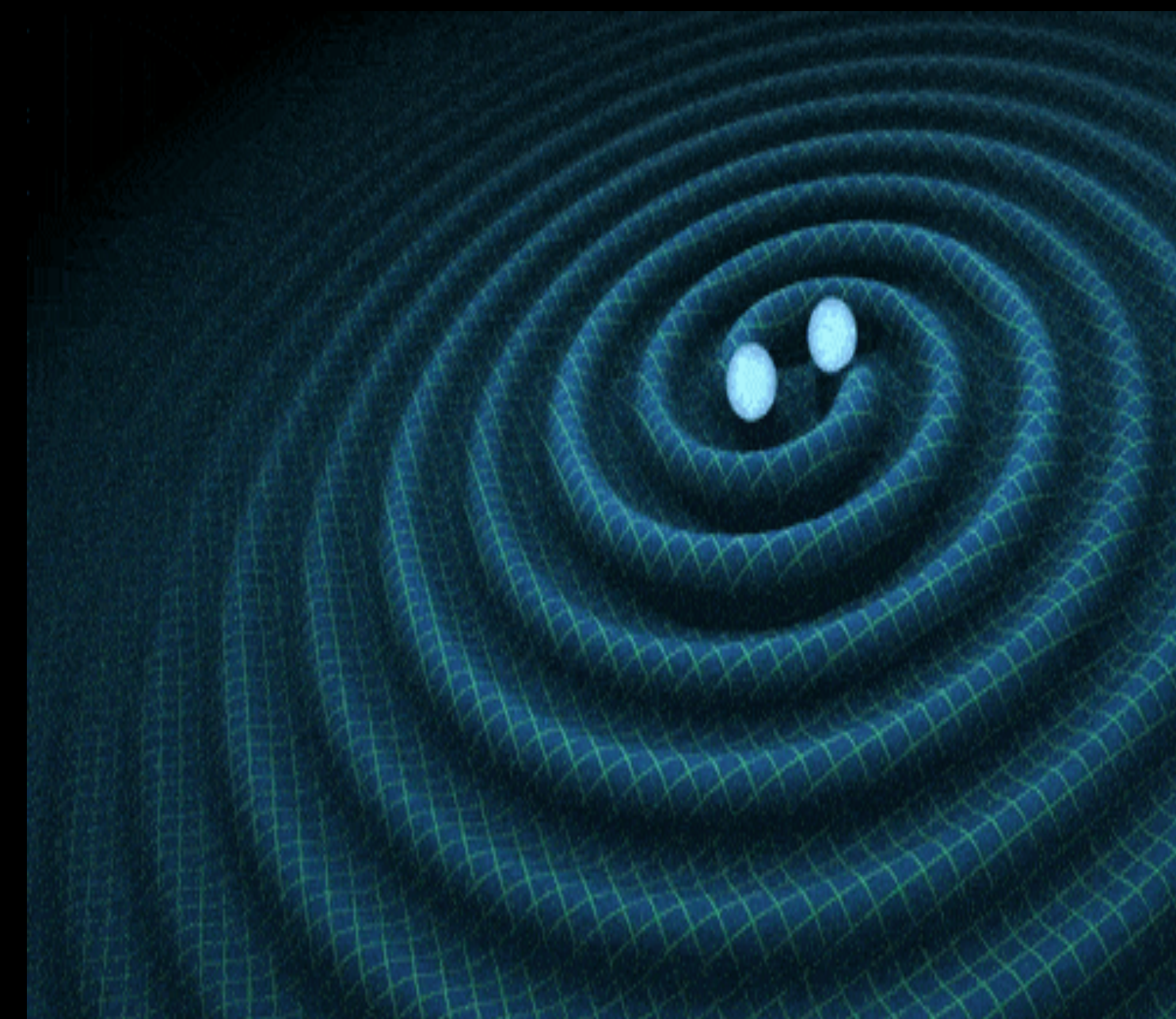


$$1 \text{ pc} \gtrsim a_b \gtrsim 10^{-2} \text{ pc}$$

Circumbinary Disk (CBD)

- Semi-major axis
- **Eccentricity**
- **Mass Ratio**
- **Spin**
- Transients

# GW emission



$$a_b \lesssim 10^{-2} \text{ pc}$$

# Post Galaxy Merger



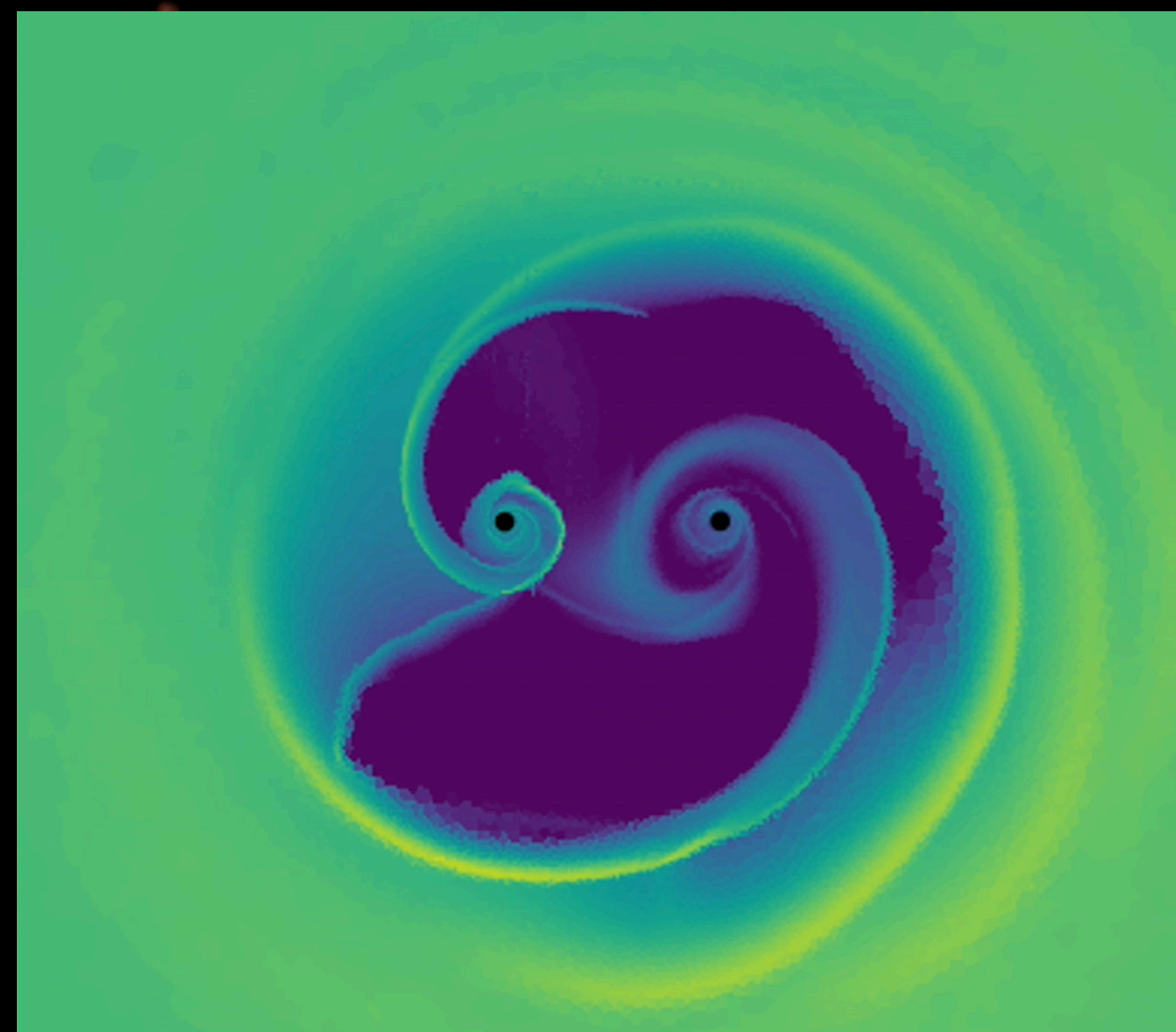
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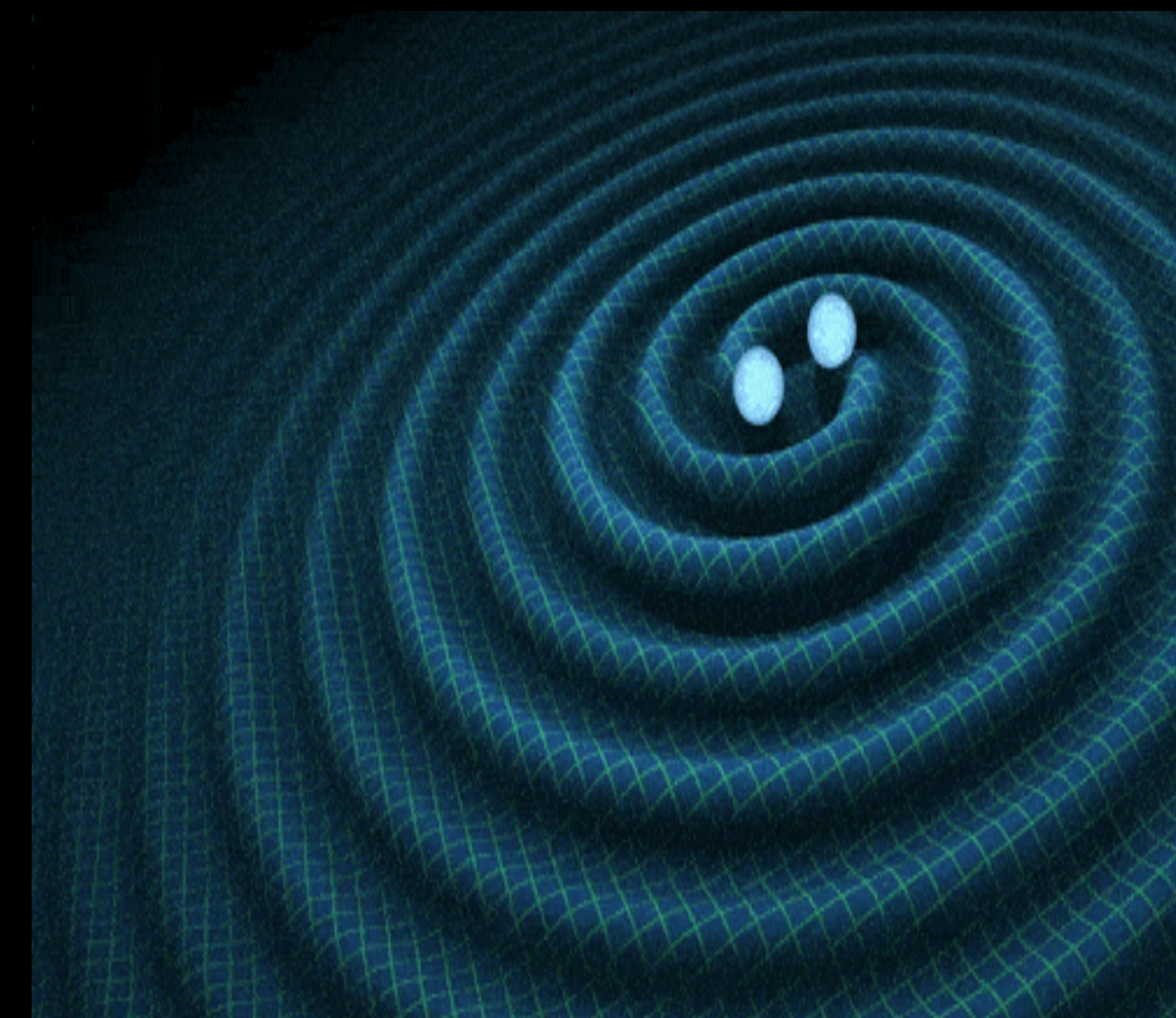


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# GW emission



$a_b \lesssim 10^{-2} \text{ pc}$

GW Hardening

- Emission of GWs: PTAs & LISA
- Evidence for GWB (e.g., NANOGrav 2023)

# Post Galaxy Merger



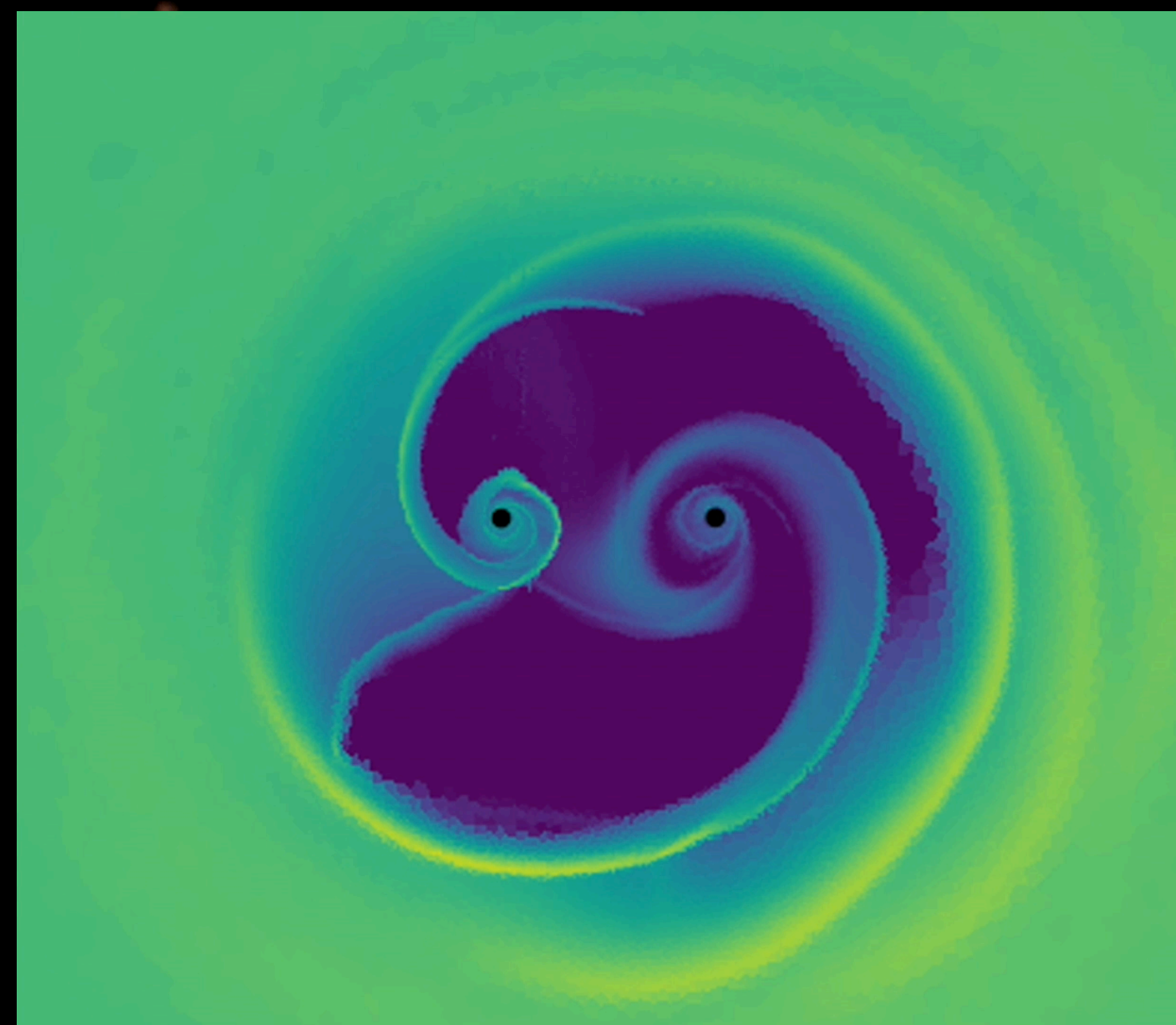
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Dynamical Friction

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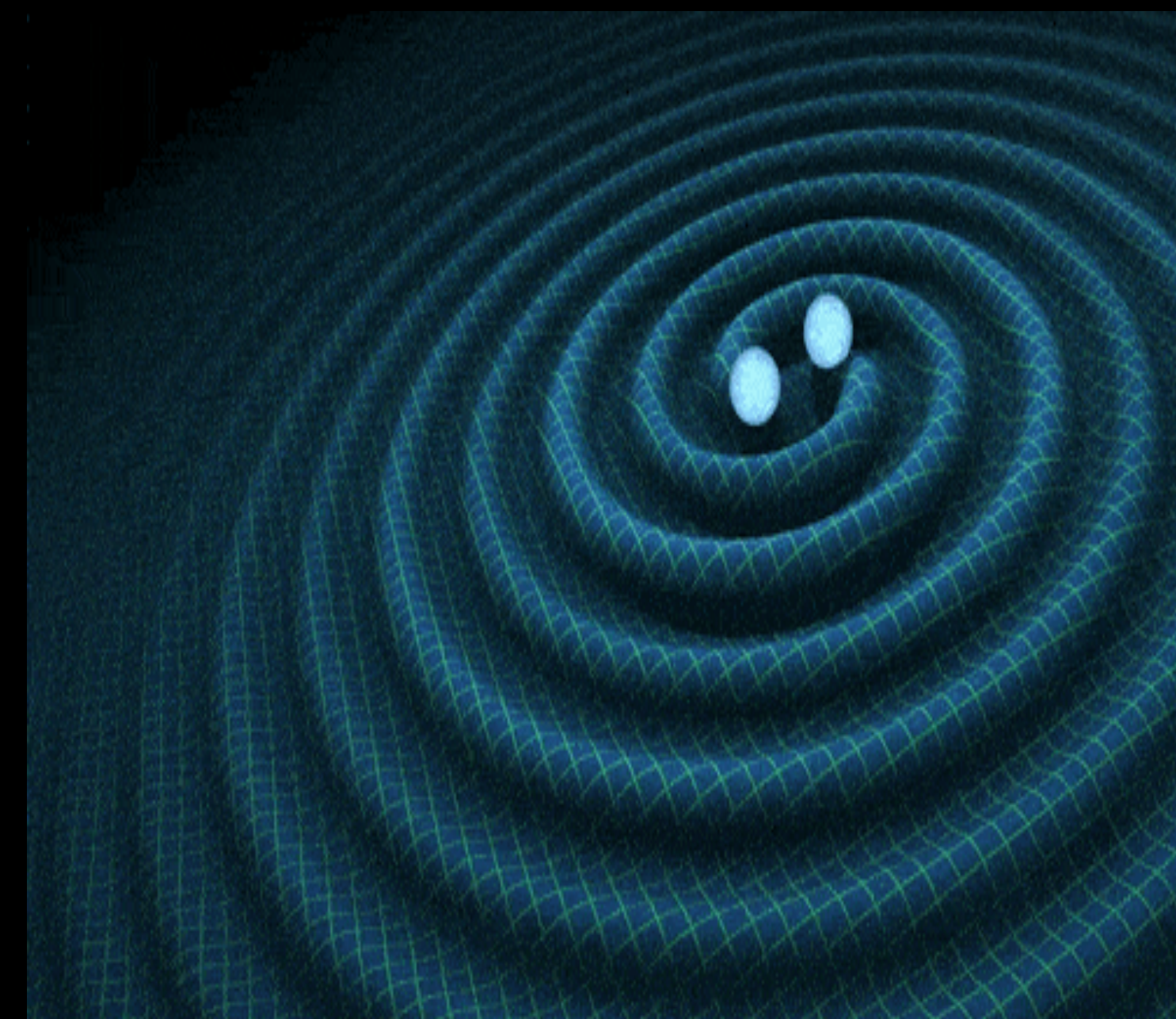


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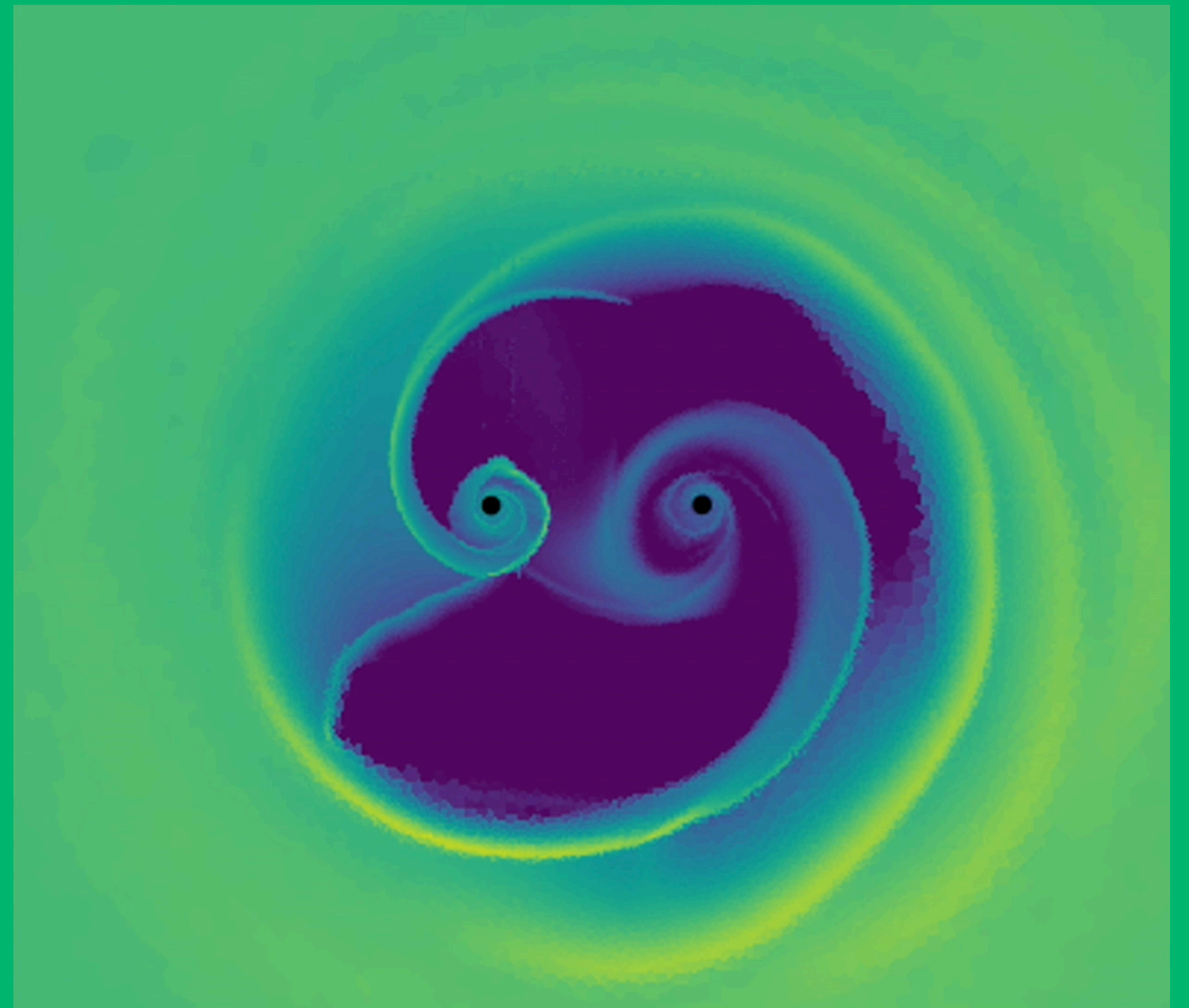
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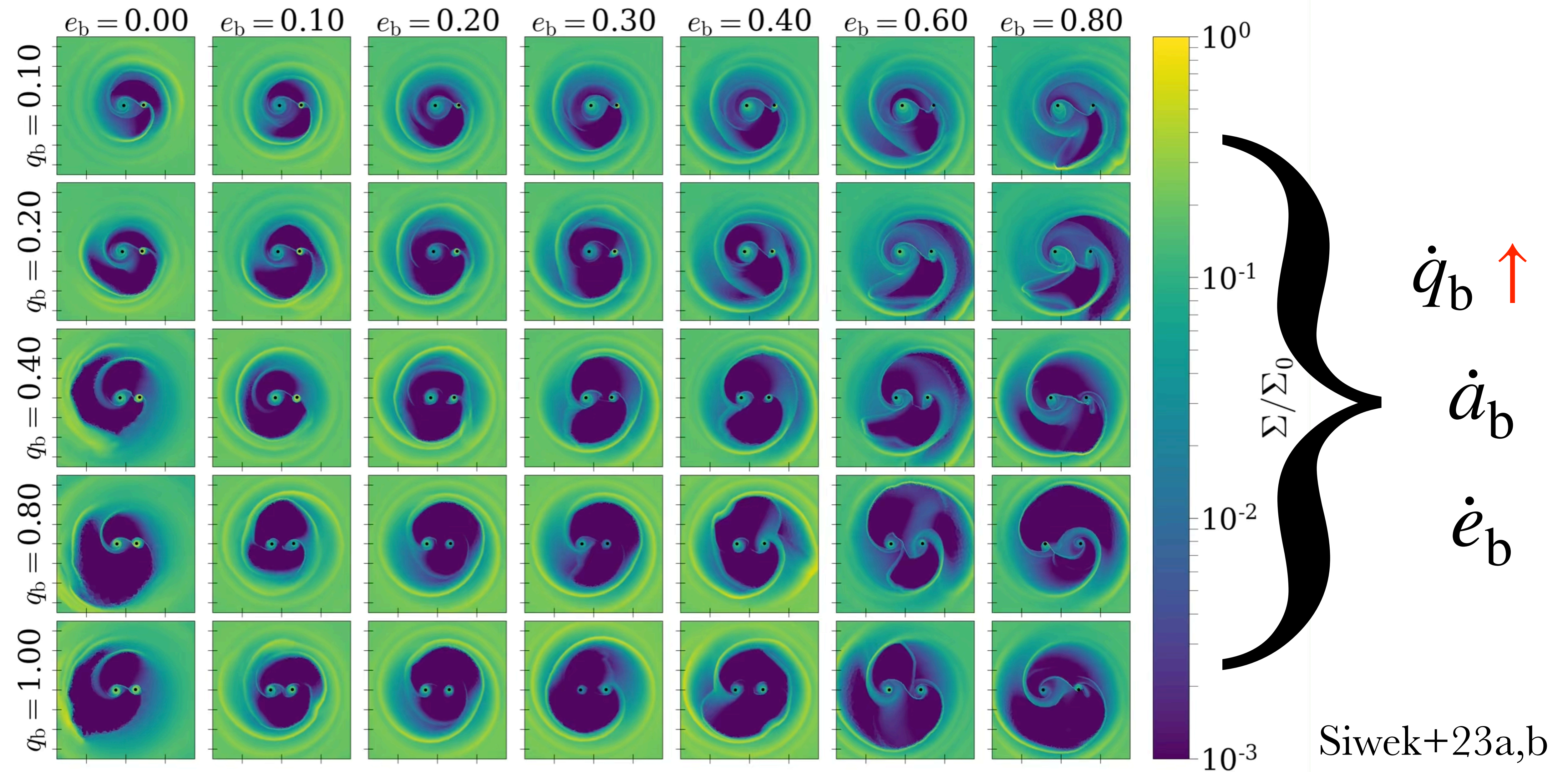


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4. Electromagnetic Signatures & CBD accretion variability



# Largest suite of Circumbinary Disk simulations to date: Binary Evolution



# A comprehensive model of Binary Evolution in Circumbinary Disks

Semi-major axis evolution

$$\dot{a}_b/a_b [\dot{M}_b/M_b], g + a$$

	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
$q_b = 0.1$	-1.28	-5.06	1.03	3.43	3.74	4.0	3.0	-6.32
$q_b = 0.2$	-0.77	-1.51	-0.16	0.92	2.87	2.59	-1.3	-7.09
$q_b = 0.3$	1.15	-2.05	-1.89	-0.19	-1.44	-0.93	-2.34	-3.49
$q_b = 0.4$	1.29	-1.3	-0.65	-2.41	-2.5	-2.93	-1.48	-3.61
$q_b = 0.5$	1.43	-0.69	-0.15	-2.43	-2.1	-3.73	-1.26	-3.52
$q_b = 0.6$	1.58	-0.69	-0.42	-2.37	-2.96	-4.33	-0.3	-2.73
$q_b = 0.7$	1.67	-0.75	-0.46	-2.38	-5.16	-4.36	0.28	-2.85
$q_b = 0.8$	1.72	-0.94	-0.67	-2.52	-6.23	-0.28	0.52	-3.0
$q_b = 0.9$	1.74	-0.88	-1.02	-4.15	-6.23	0.86	0.47	-2.89
$q_b = 1.0$	1.76	-0.95	-1.31	-4.79	-6.1	0.6	0.38	-2.74

Hardening/Softening

Eccentricity evolution

$$\dot{e}_b [\dot{M}_b/M_b], g + a$$

	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
$q_b = 0.1$	0.0	1.55	0.78	-1.84	-4.15	-4.78	-5.95	-7.7
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$q_b = 0.3$	0.0	3.73	5.59	0.23	-0.4	-2.73	-3.95	-3.46
$q_b = 0.4$	0.0	4.29	3.5	2.52	0.23	-1.64	-2.81	-2.61
$q_b = 0.5$	-0.0	4.33	3.75	3.38	1.33	-1.82	-2.37	-2.15
$q_b = 0.6$	0.0	4.73	4.9	4.52	3.33	-0.04	-2.2	-1.96
$q_b = 0.7$	0.0	4.88	5.48	5.26	5.6	0.58	-2.14	-1.86
$q_b = 0.8$	-0.0	5.28	5.95	5.97	6.48	-1.15	-2.08	-1.7
$q_b = 0.9$	-0.0	5.16	6.6	8.33	7.02	-1.83	-2.12	-1.69
$q_b = 1.0$	0.0	5.33	7.07	9.43	6.91	-1.67	-2.11	-1.85

Circularizing/Eccentricity Growth

See also: Gould & Rix 2000; Armitage & Natarajan 2002, 2005; Cuadra+2009; Haiman+2009; Chang+2010; Farris+2015, Miranda+2017; Tang+2017; Moody+2019; Muñoz+2019; Duffell+2020; Muñoz+2020, Tiede+2020; Duffell+2020; Franchini+21,22, Zrake+2021, D’Orazio & Duffell 2021, ...

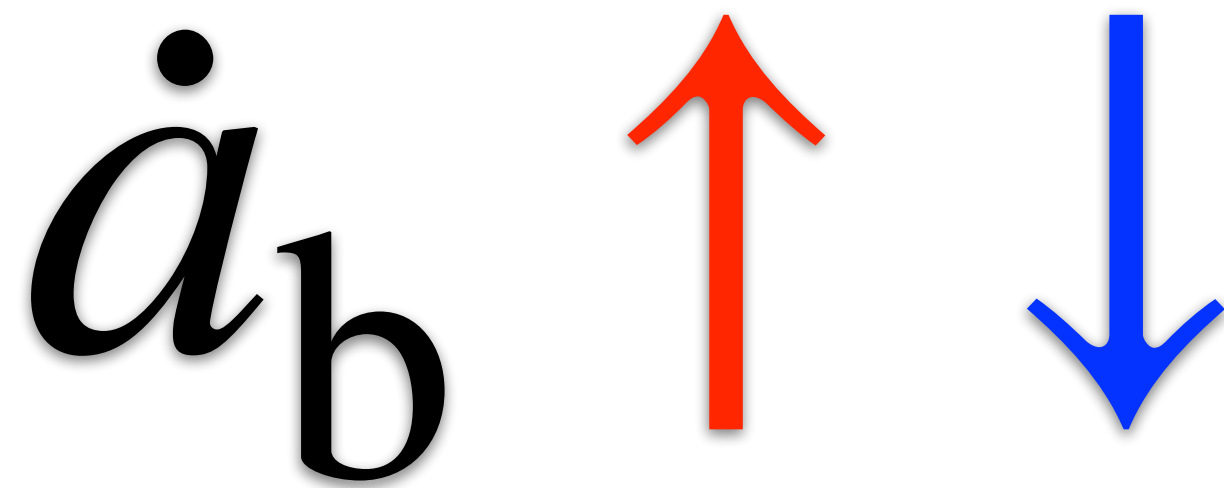
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Hardening/Softening



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$$\dot{e}_b [\dot{M}_b/M_b], g + a$$

	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
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Circularizing/Eccentricity Growth

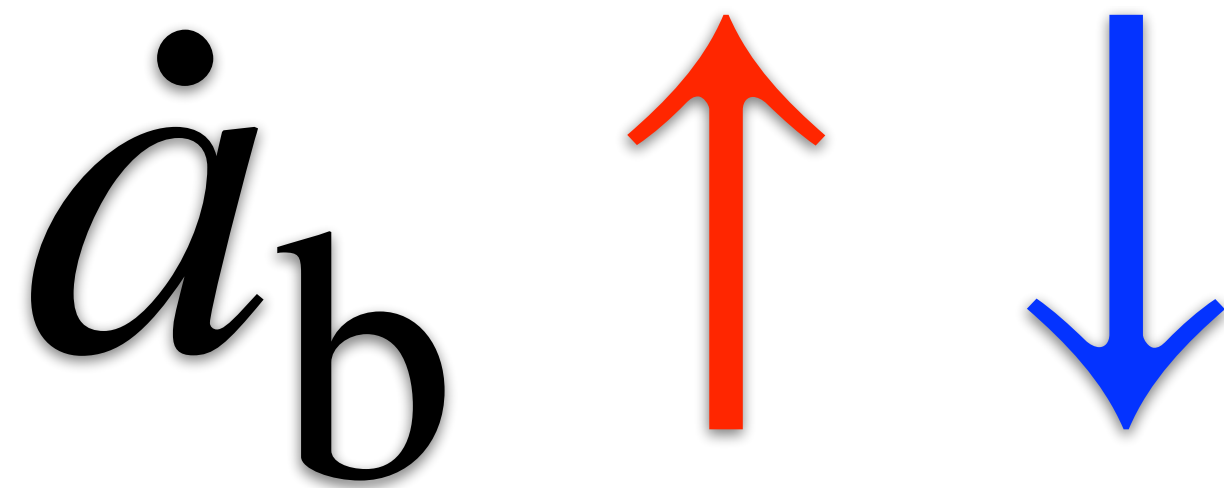
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Hardening/Softening



Eccentricity evolution

$$\dot{e}_b [\dot{M}_b/M_b], g + a$$

	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
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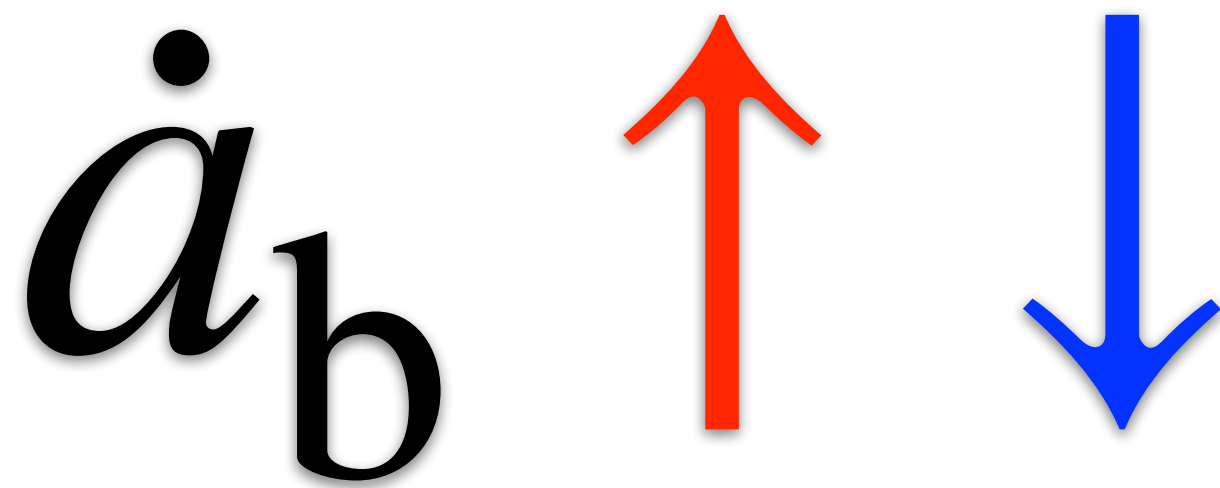
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Eccentricity evolution

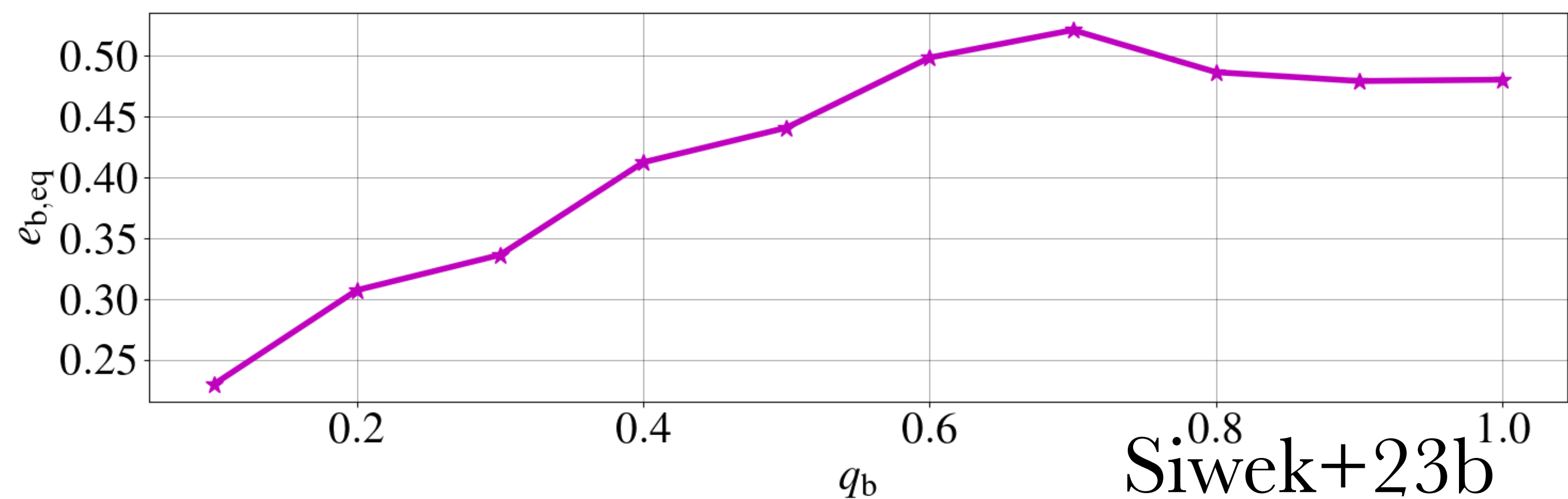
$$\dot{e}_b [\dot{M}_b/M_b], g + a$$

	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
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Hardening/Softening

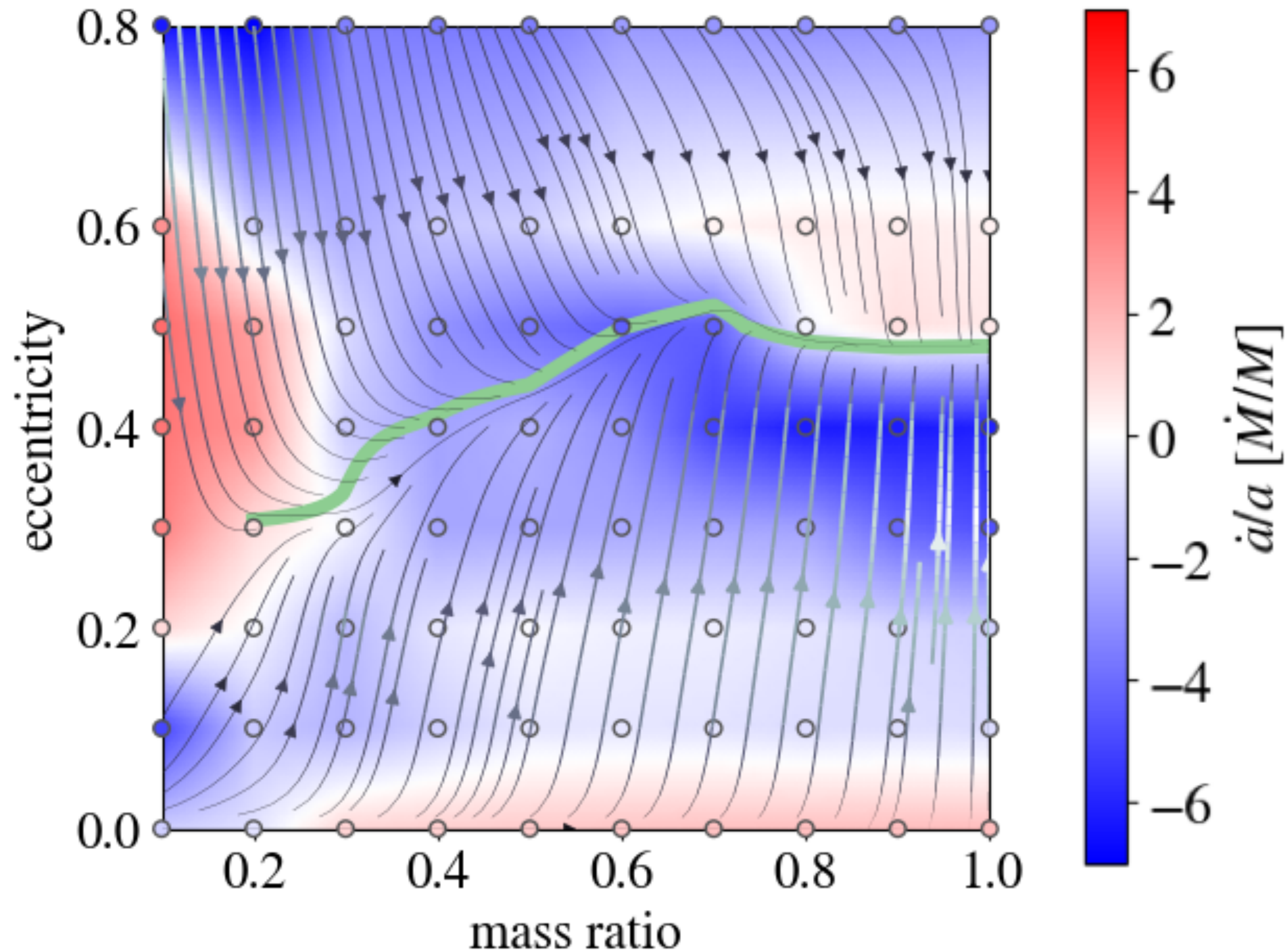


Circularizing/Eccentricity Growth



Siwek+23b

# Binaries evolve towards equilibrium eccentricity (Siwek+23b)

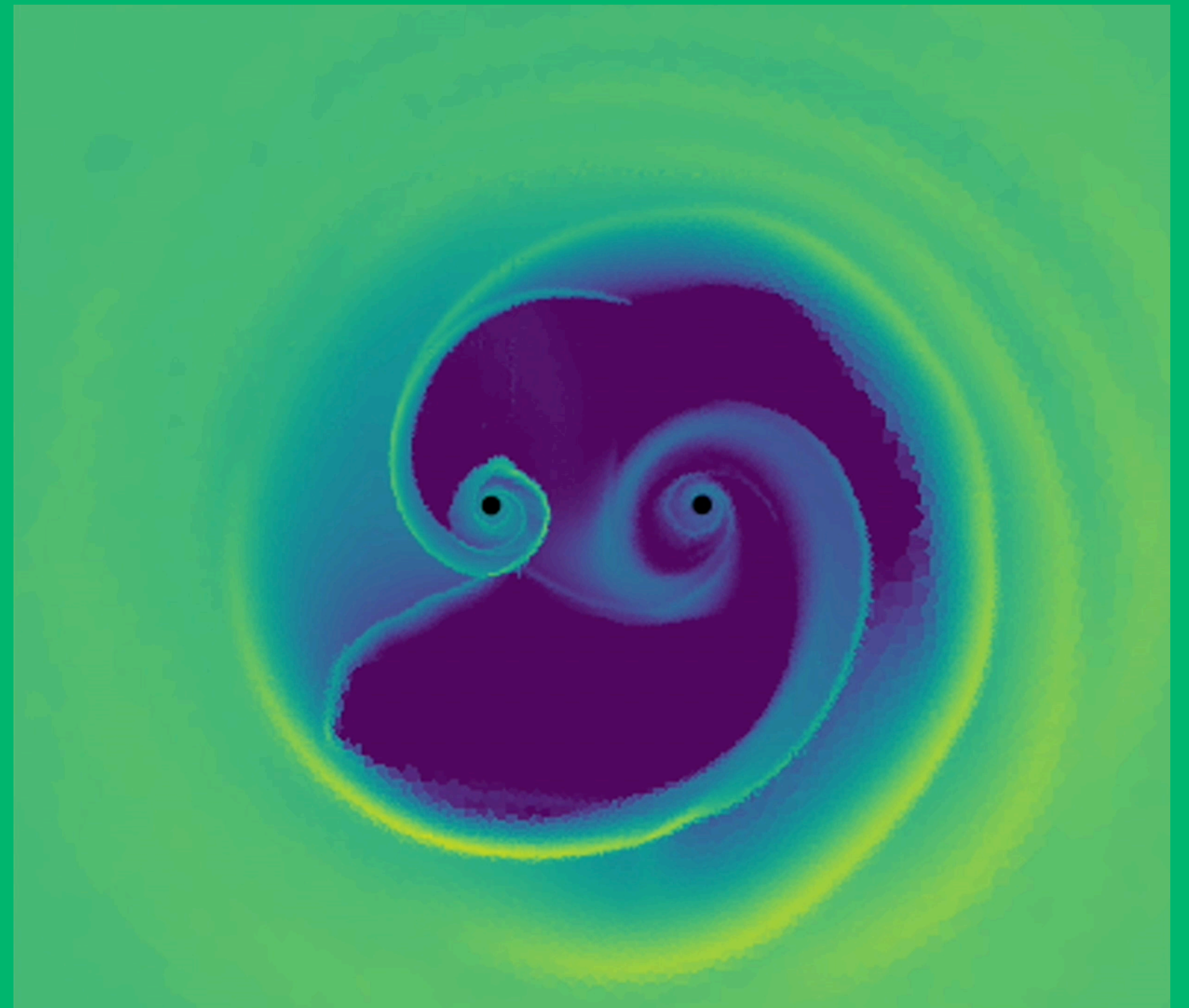


Ruggero Valli  
(MPA)  
Made this  
awesome plot!

Valli+24  
(in prep)

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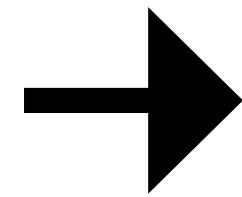




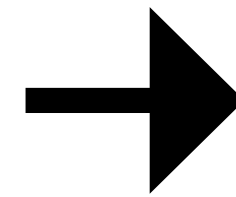
# holodeck: Population Synthesis of MBHB systems

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM  
(Kelley+ in prep)

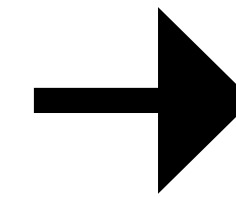
Dynamical  
Friction



Stellar  
Scattering



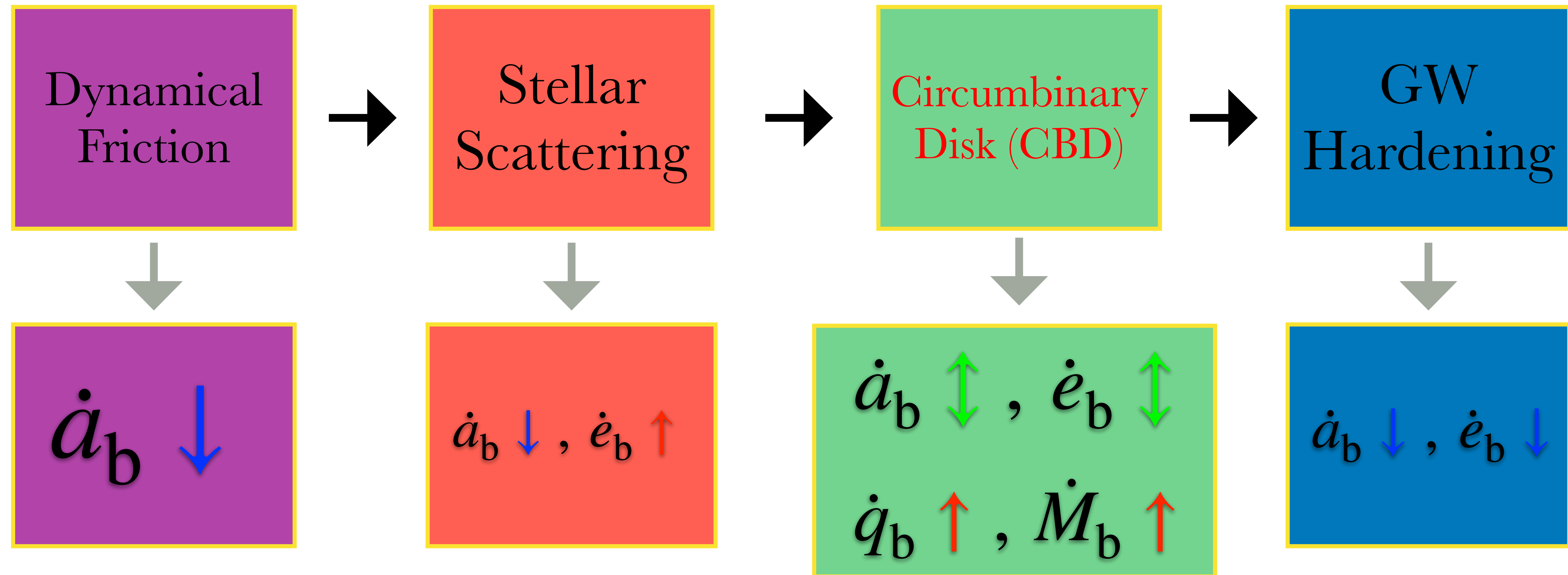
Circumbinary  
Disk (CBD)



GW  
Hardening

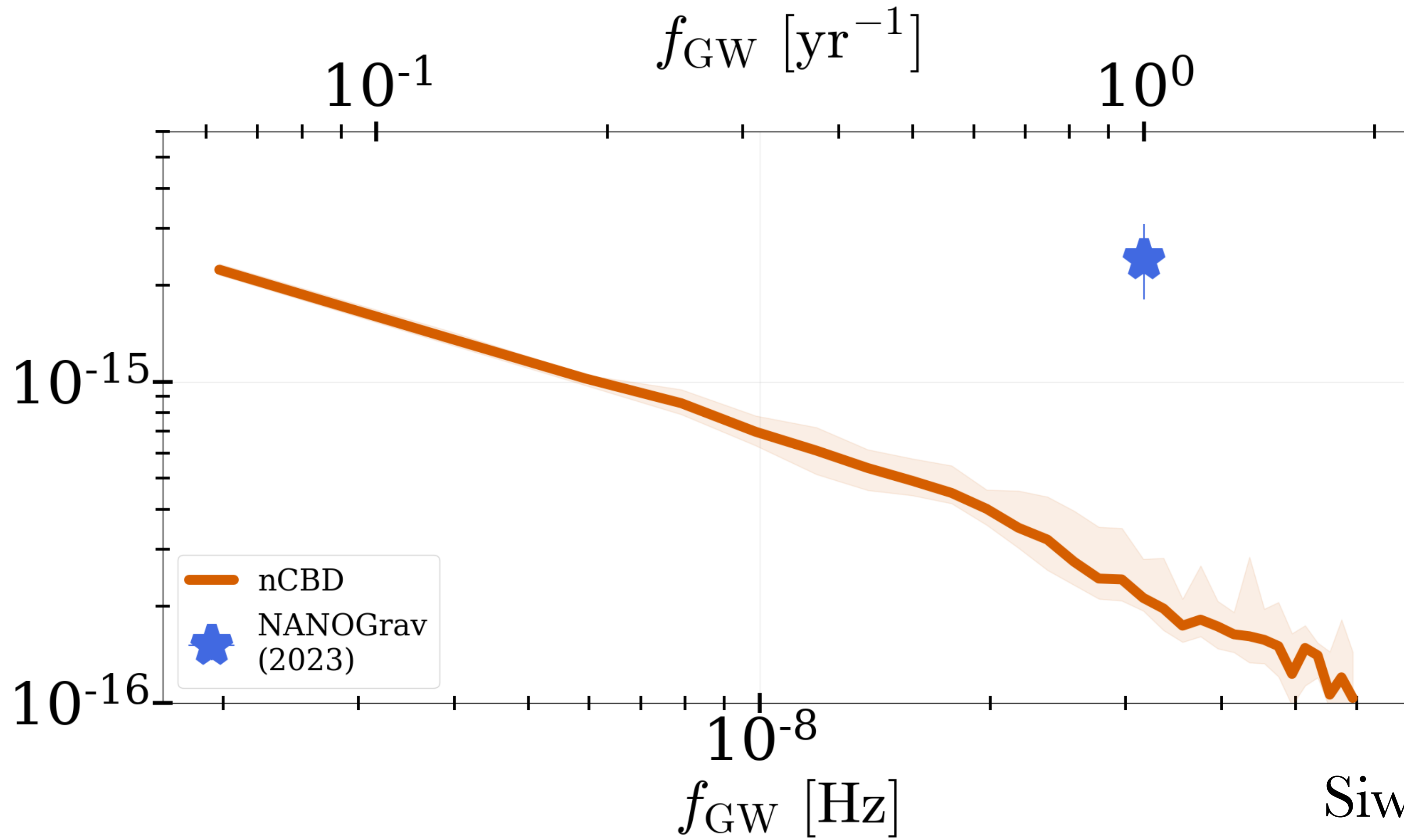
# holodeck: Population Synthesis of MBHB systems

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM  
(Kelley+ in prep)



# CBD accretion: Effect on GWB Amplitude

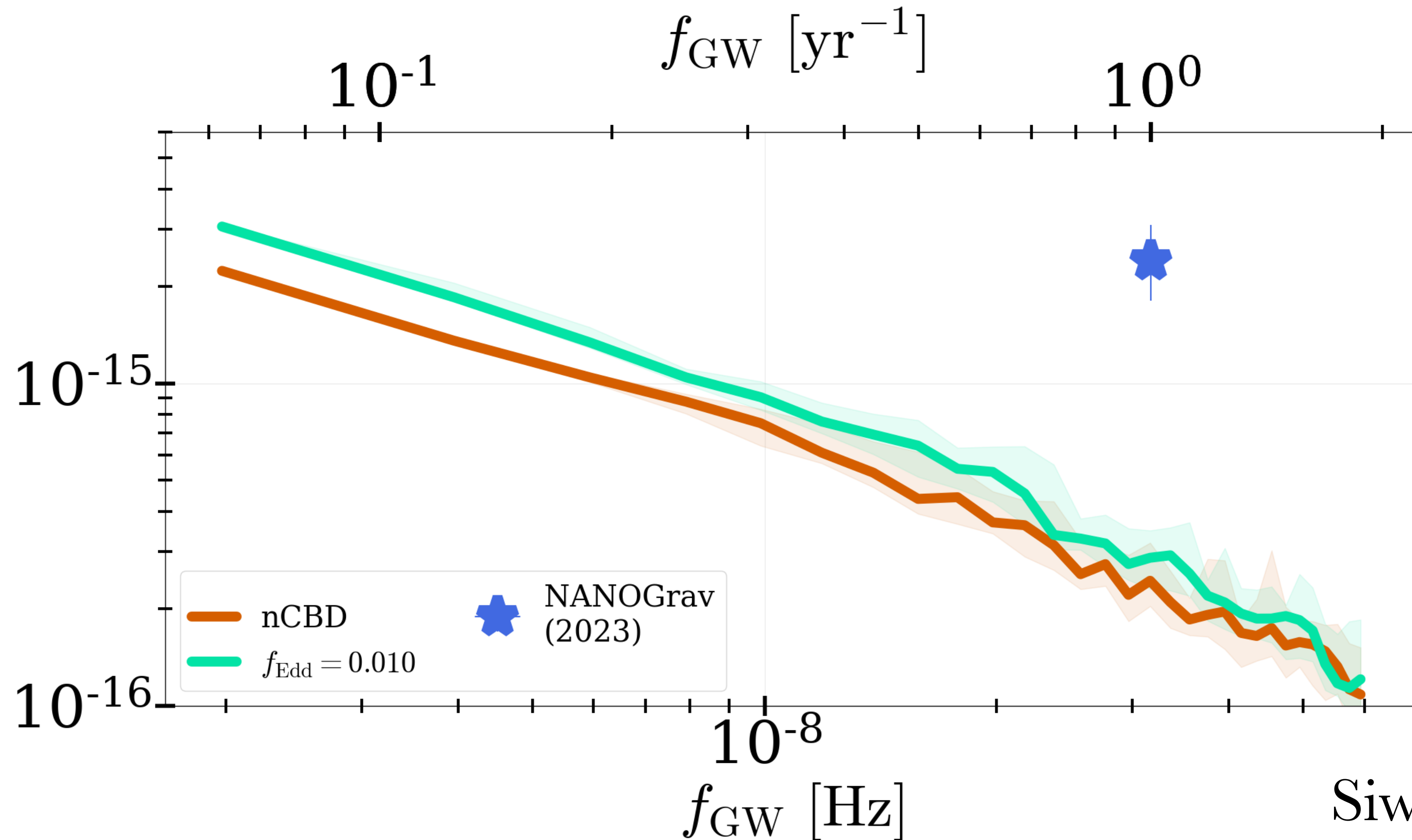
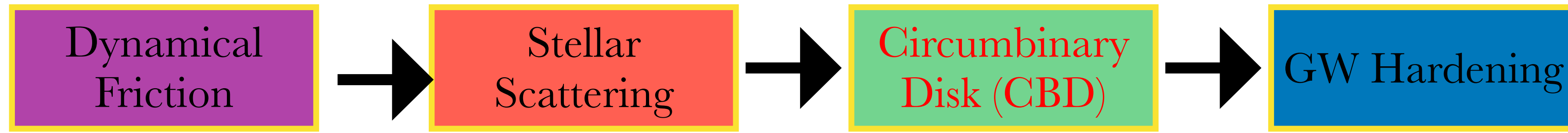
**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



Siwek+24 (in prep)

# CBD accretion: Effect on GWB Amplitude

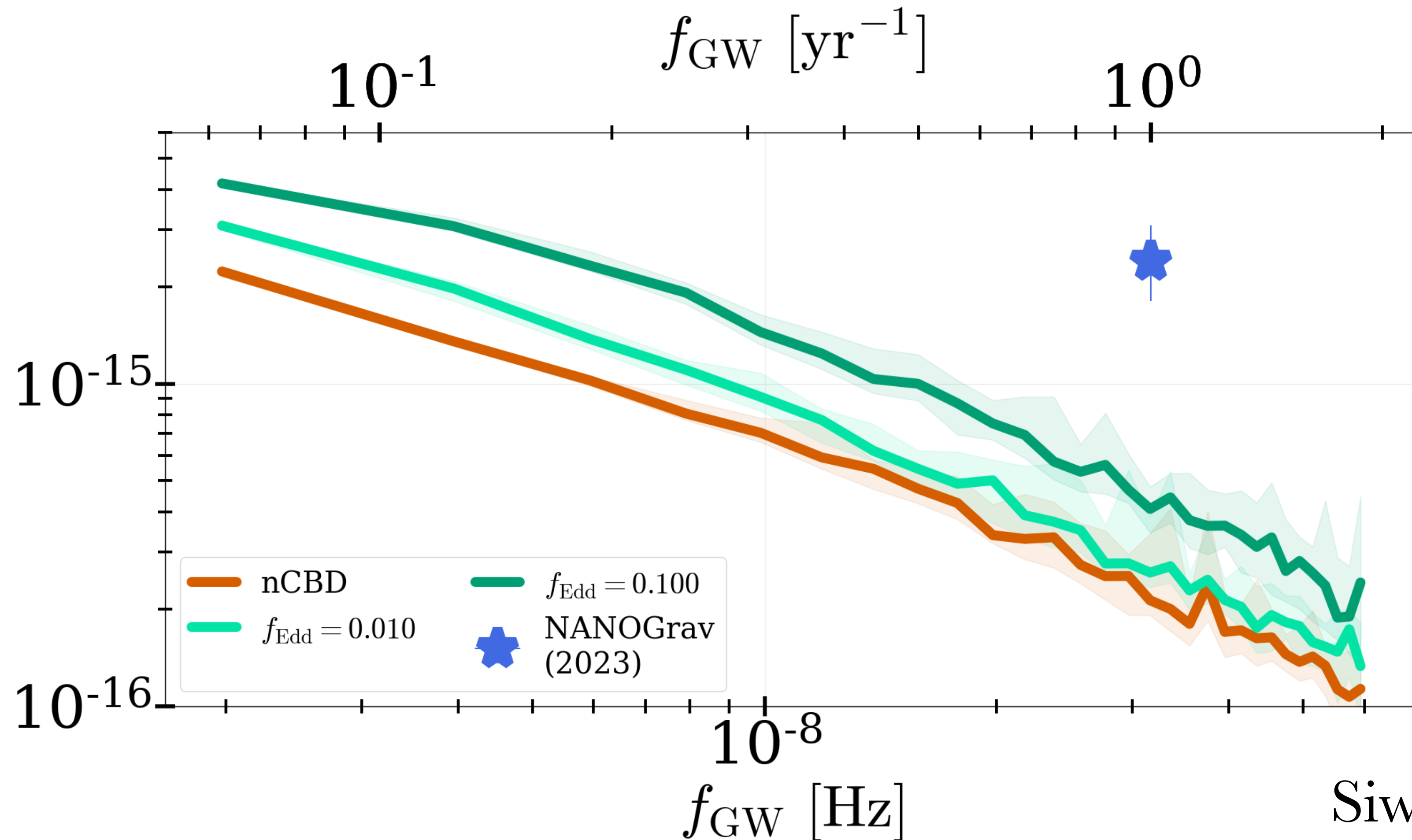
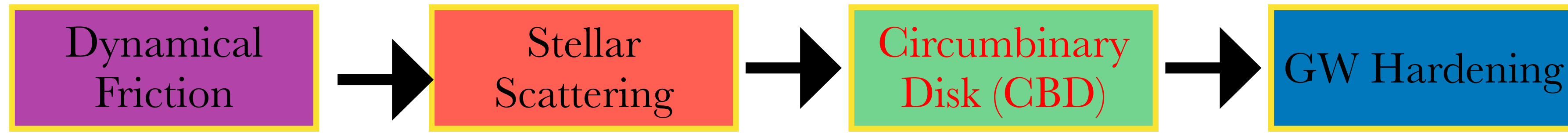
**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



Siwek+24 (in prep)

# CBD accretion: Effect on GWB Amplitude

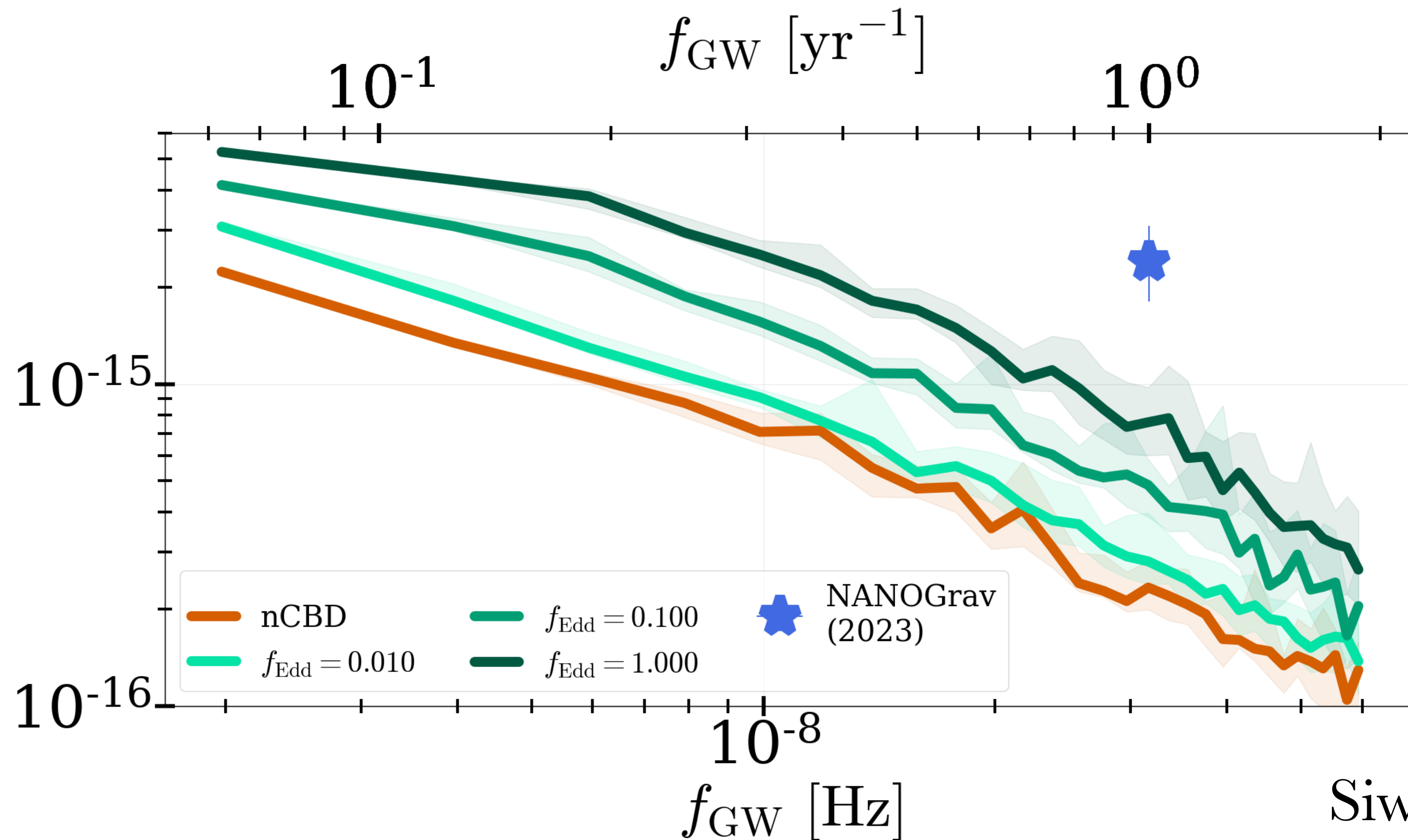
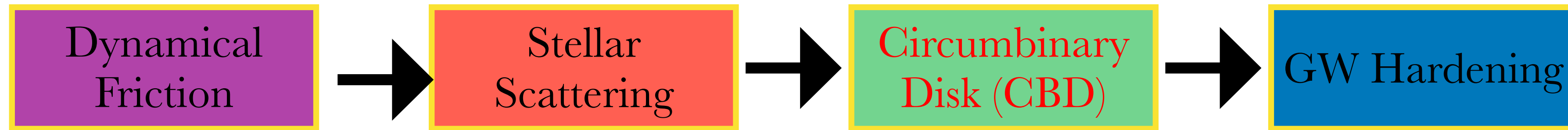
**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



Siwek+24 (in prep)

# CBD accretion: Effect on GWB Amplitude

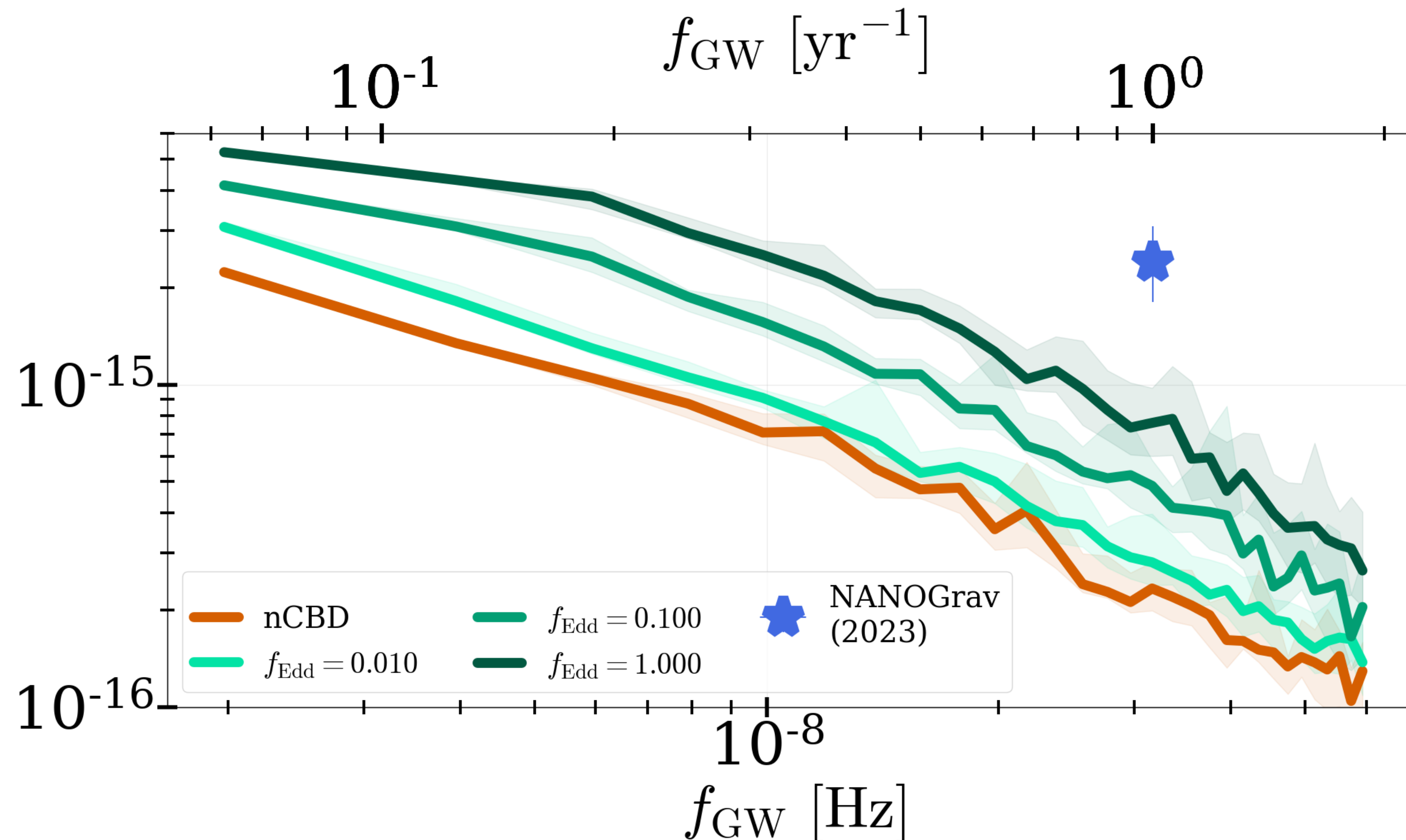
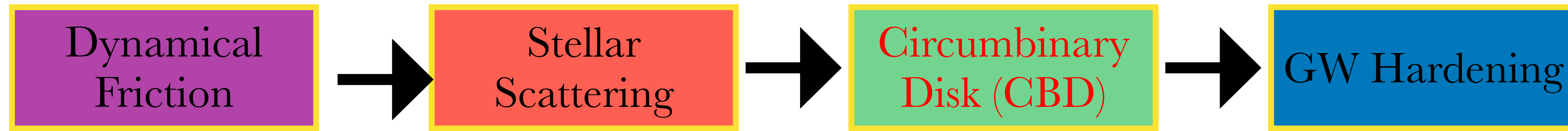
**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



Siwek+24 (in prep)

# CBD accretion: Effect on GWB Amplitude

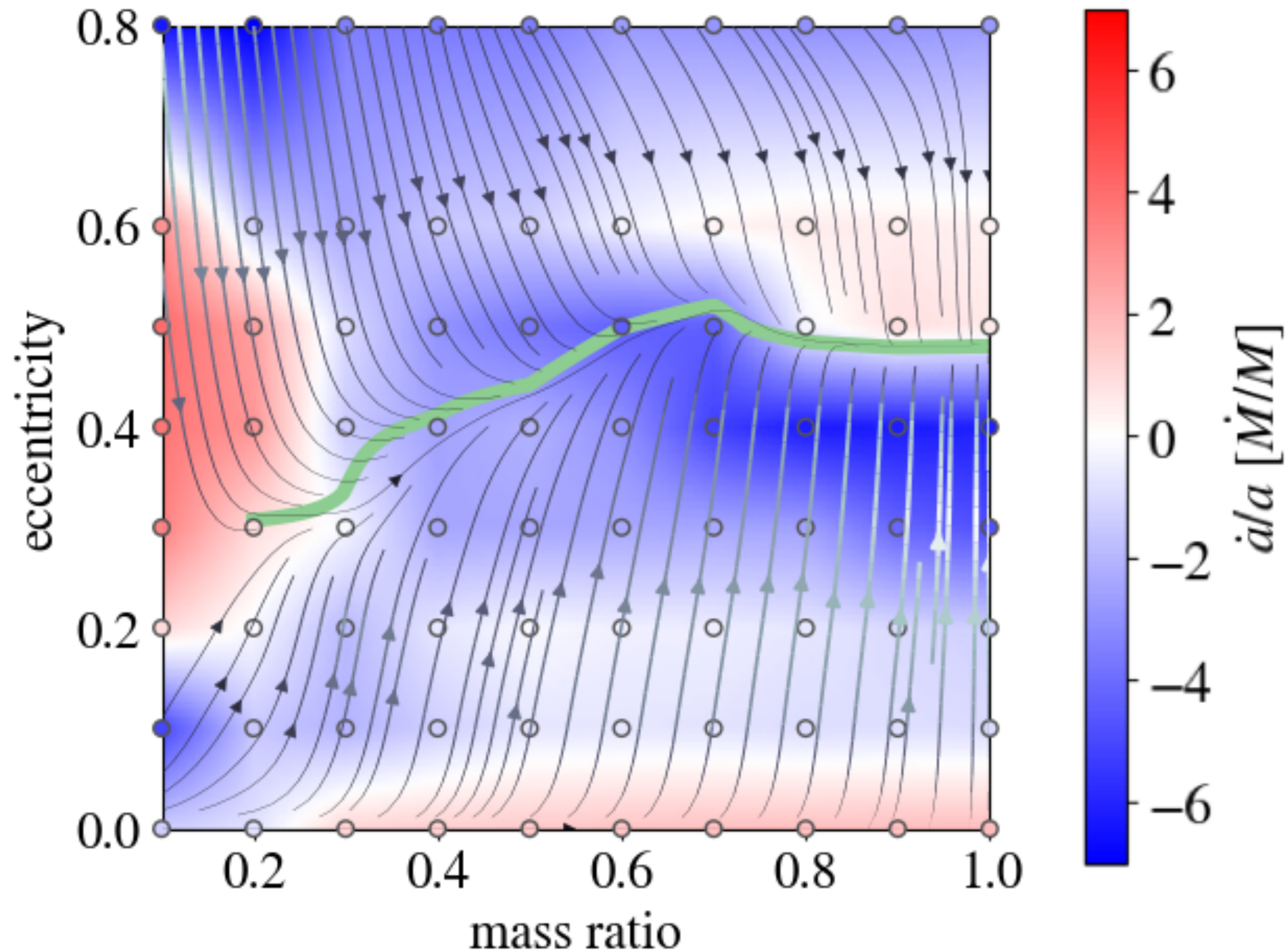
2749 MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



Accretion on secondary  
↓  
Increase in Chirp Mass  
↓  
Boost GWB amplitude by 5x

Siwek+24 (in prep)

# Binaries evolve towards equilibrium eccentricity (Siwek+23b)



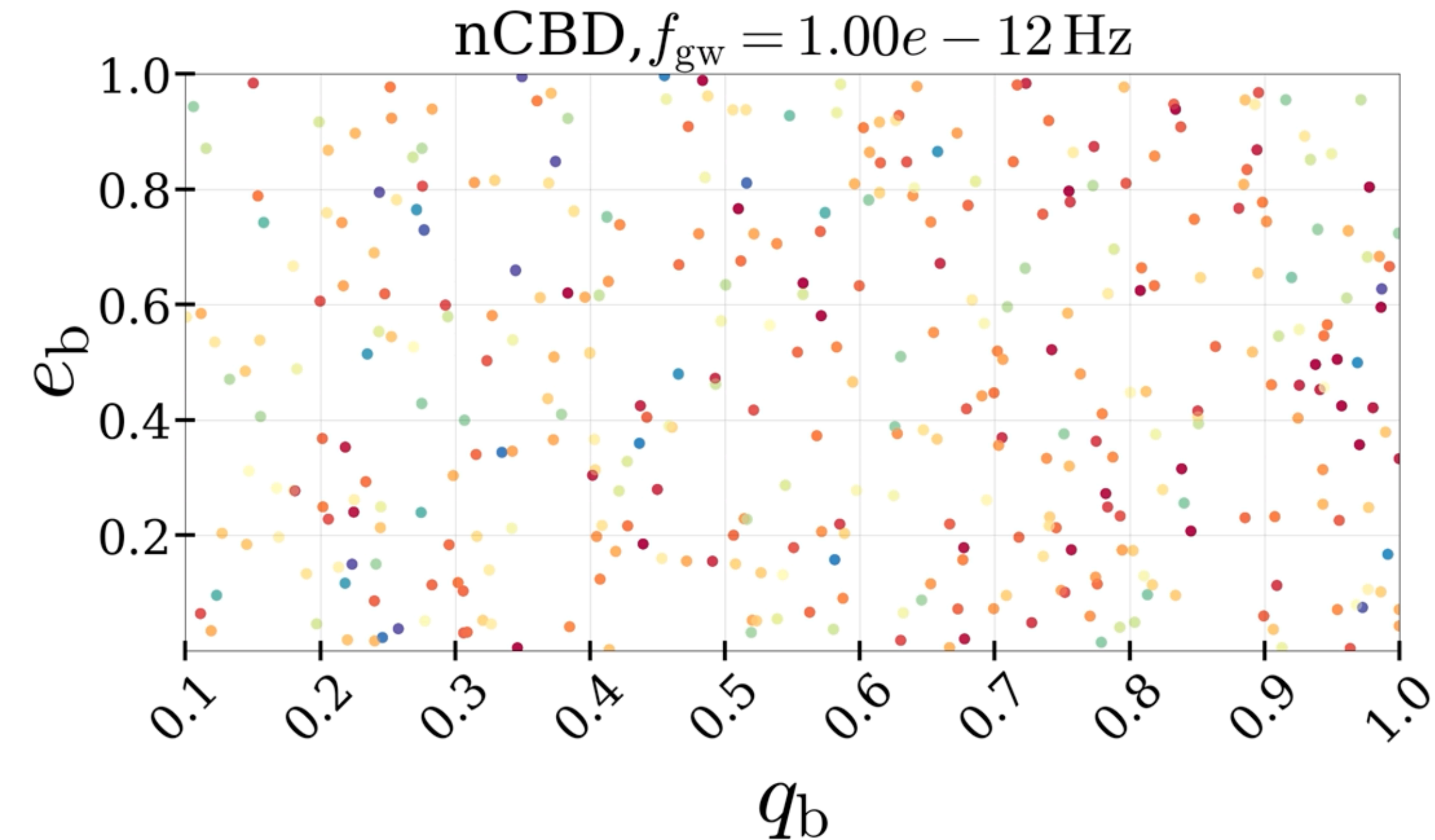
Ruggero Valli  
(MPA)  
Made this  
awesome plot!

Valli+24  
(in prep)



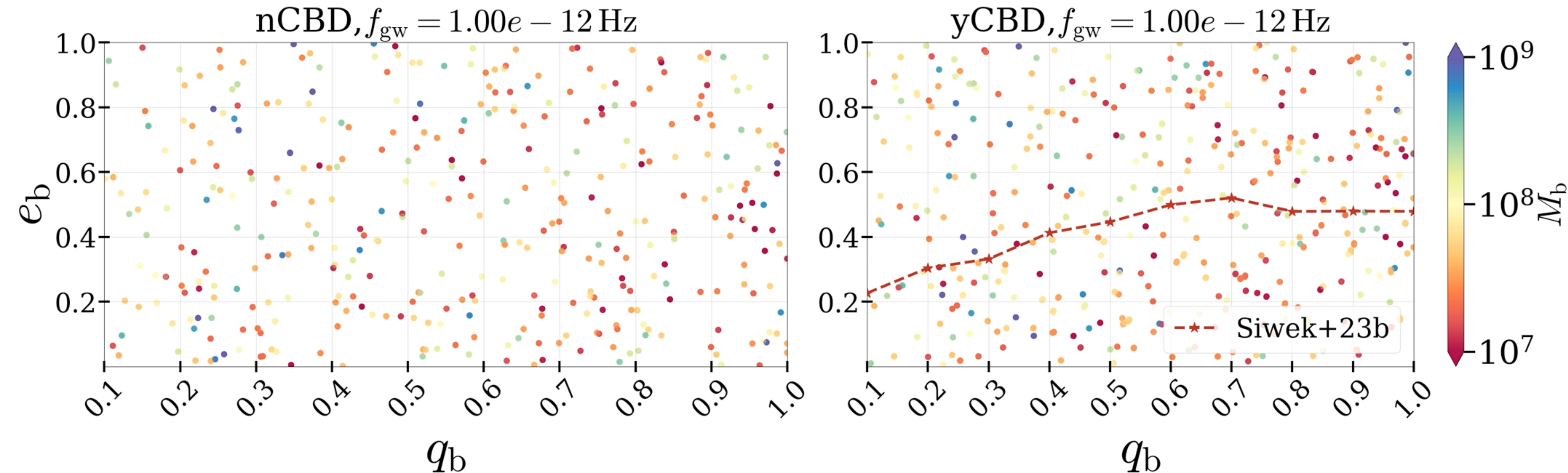
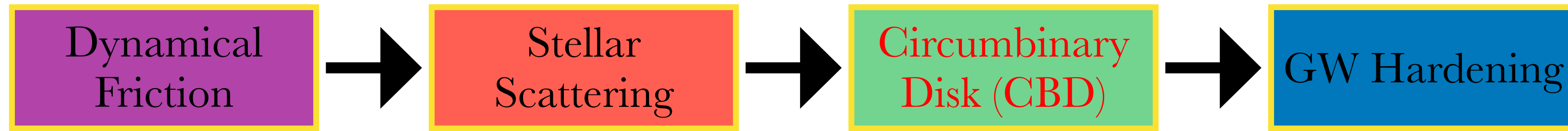
# Eccentricity evolution of MBHBs across frequency

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



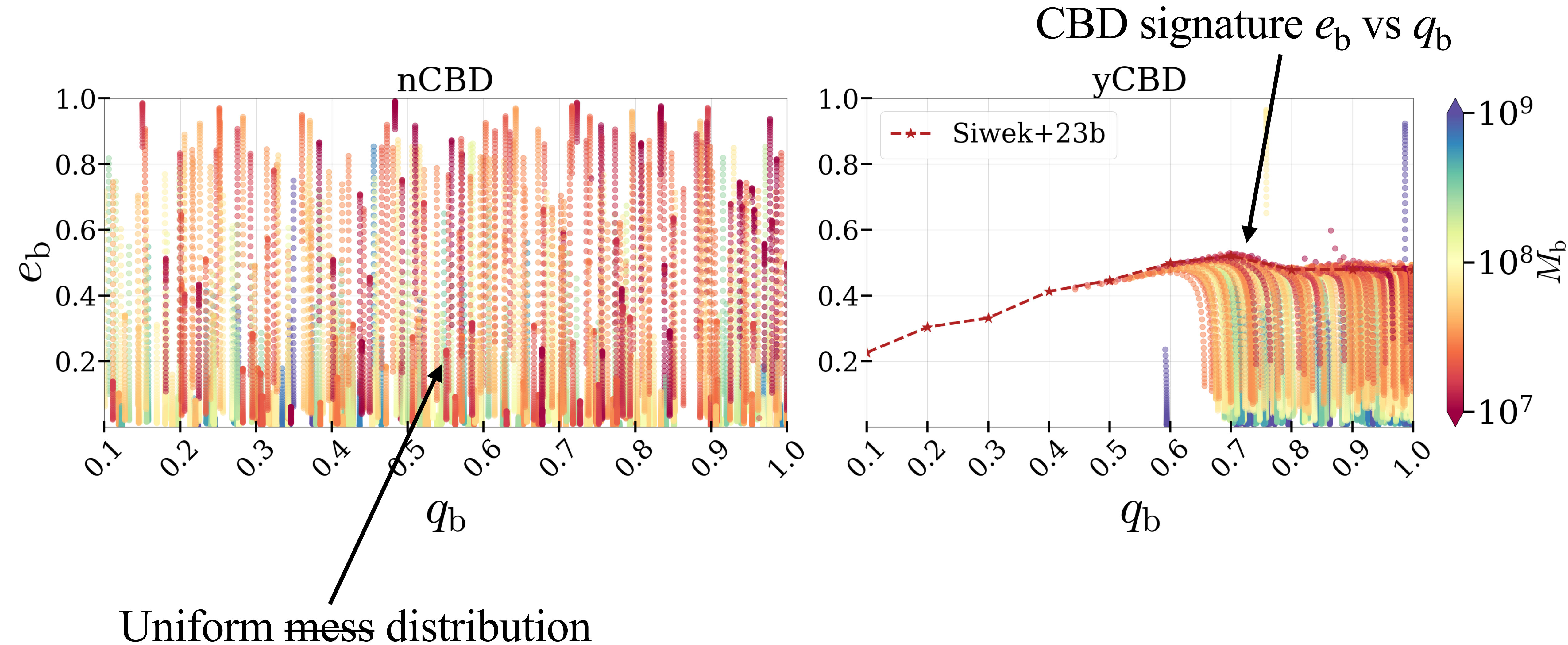
# Eccentricity evolution of MBHBs across frequency

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



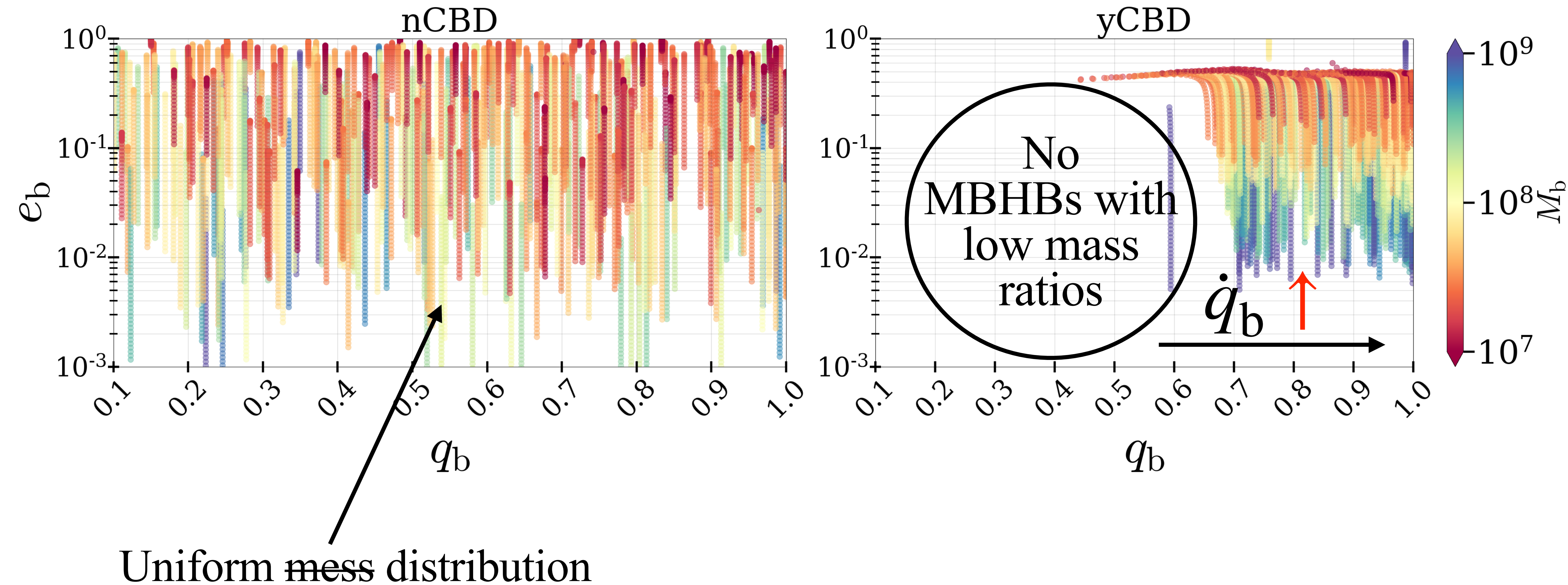
Siwek+24 (in prep)

# Eccentricity distribution of MBHBs in LSST & PTA

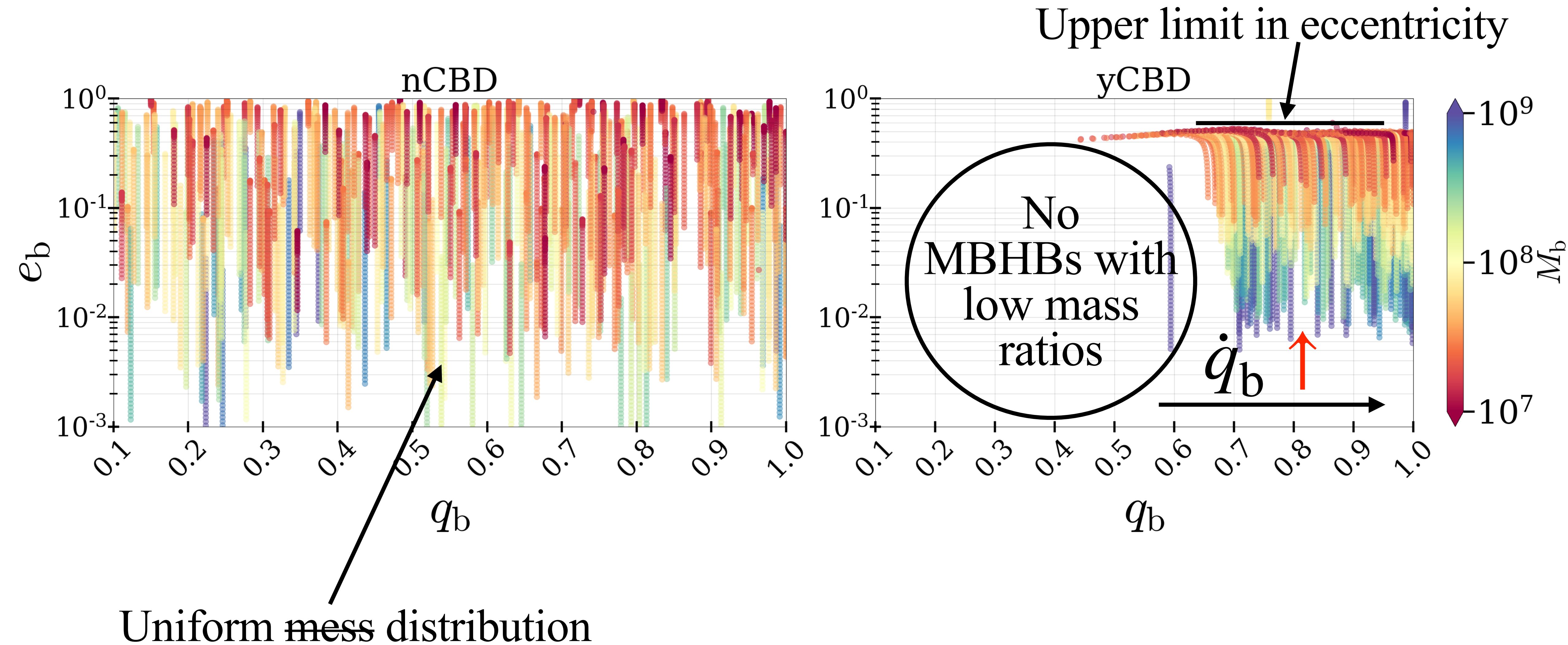


Siwek+24 (in prep)

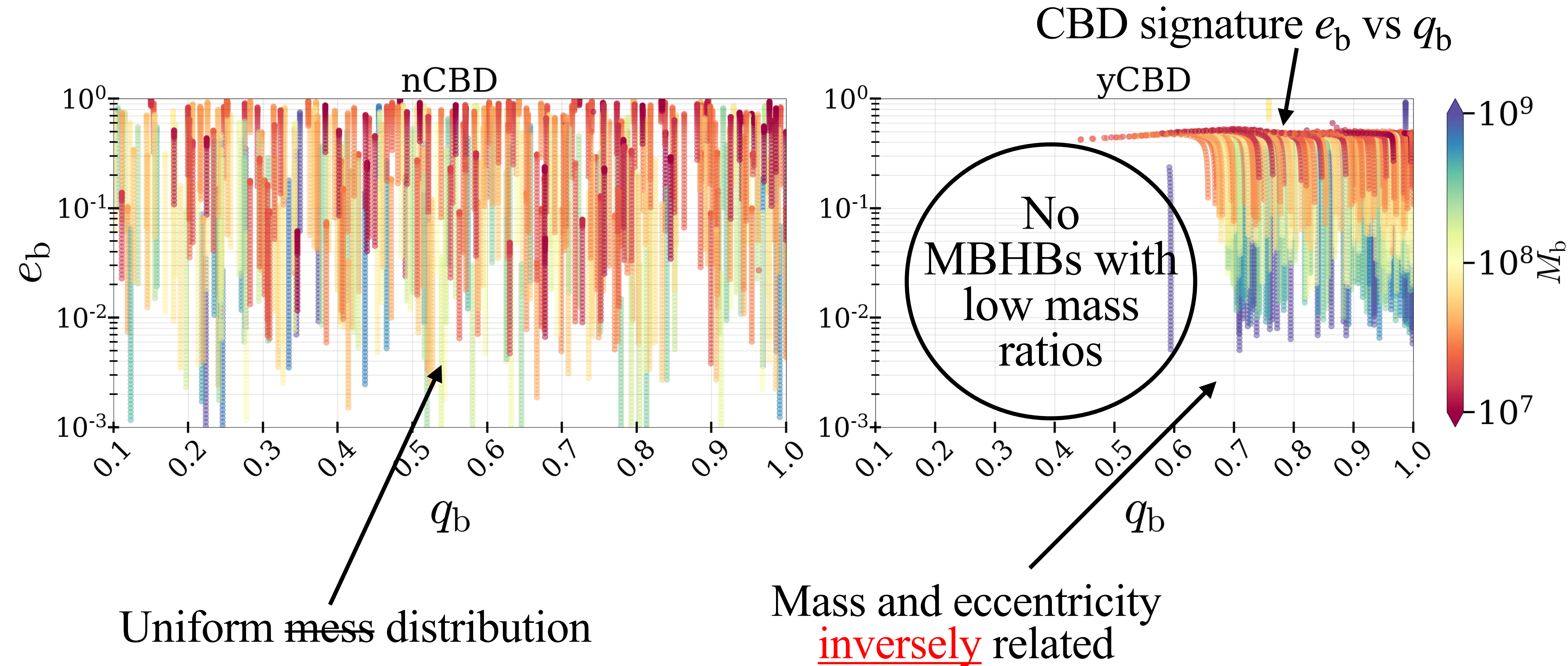
# Eccentricity distribution of MBHBs in LSST & PTA



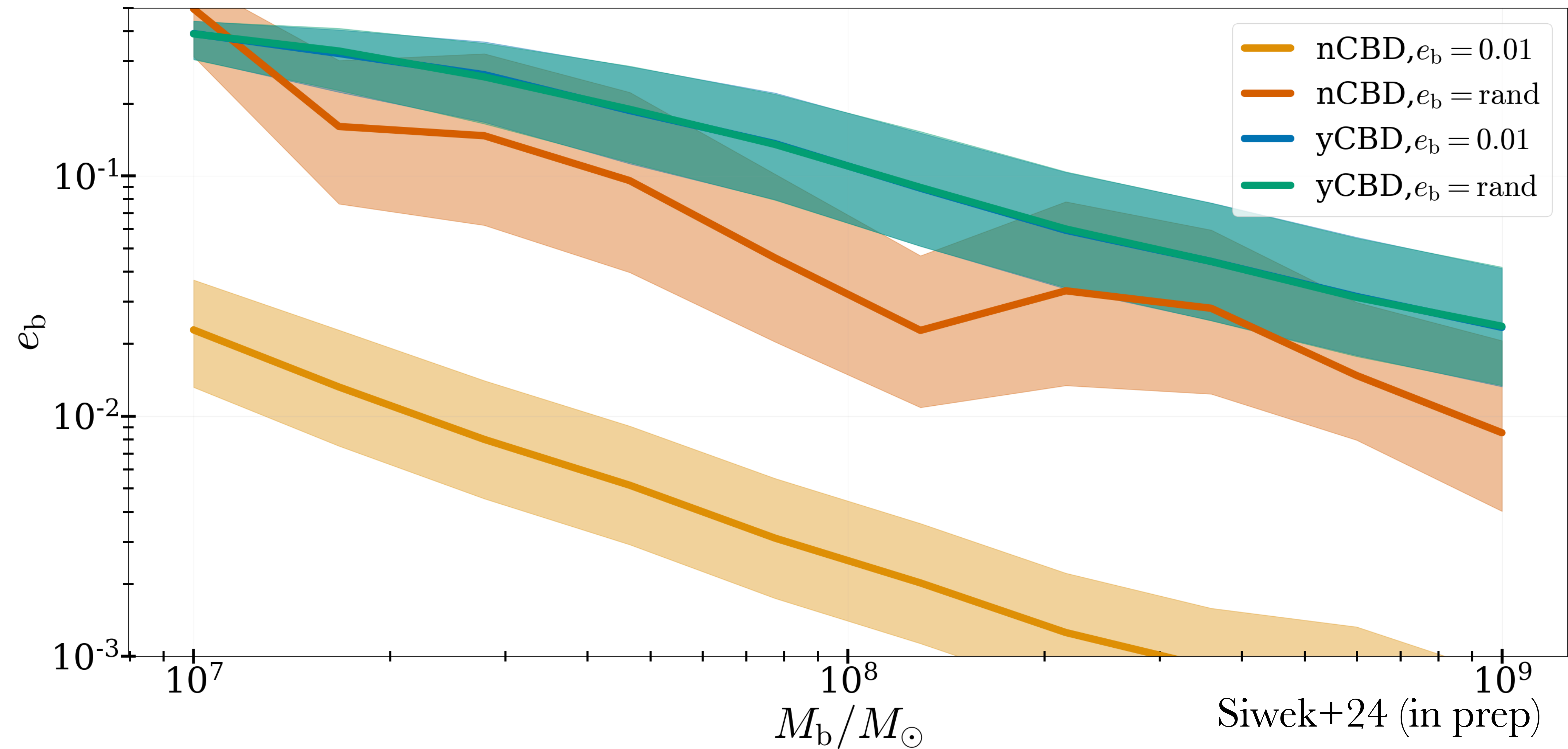
# Eccentricity distribution of MBHBs in LSST & PTA



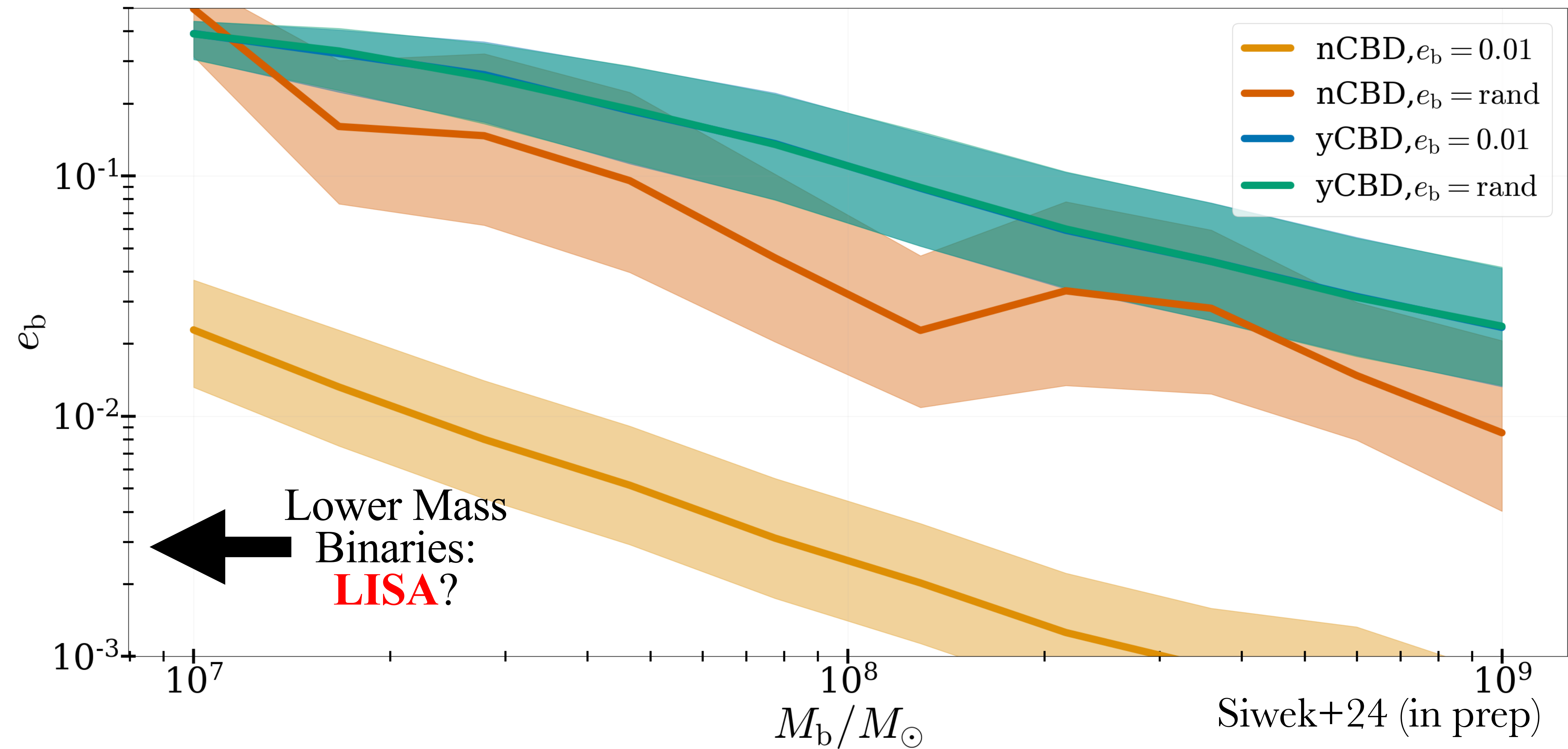
# Eccentricity distribution of MBHBs in LSST & PTA



# Eccentricity vs Mass in **LSST** MBHBs



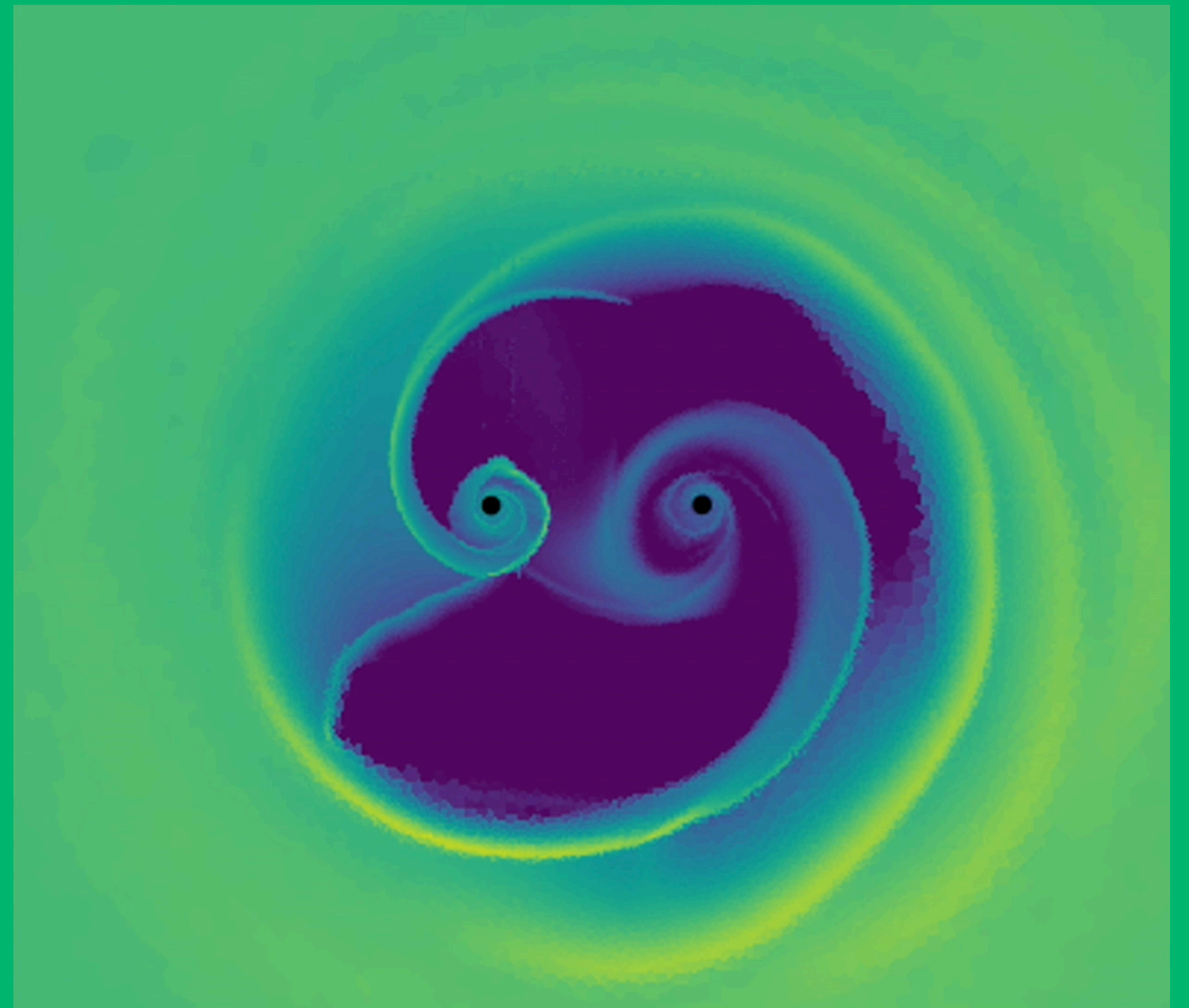
# Eccentricity vs Mass in **LSST** MBHBs



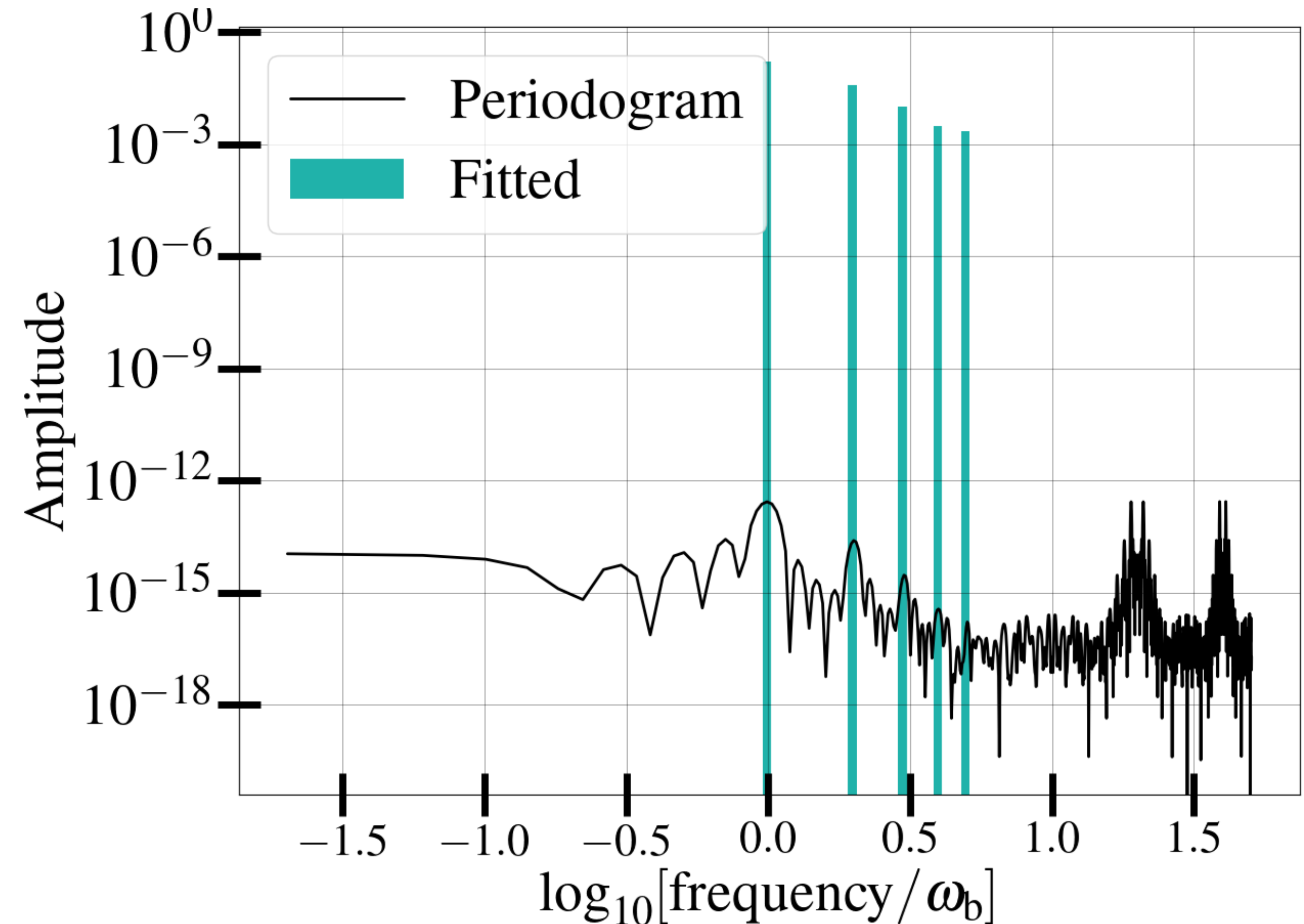
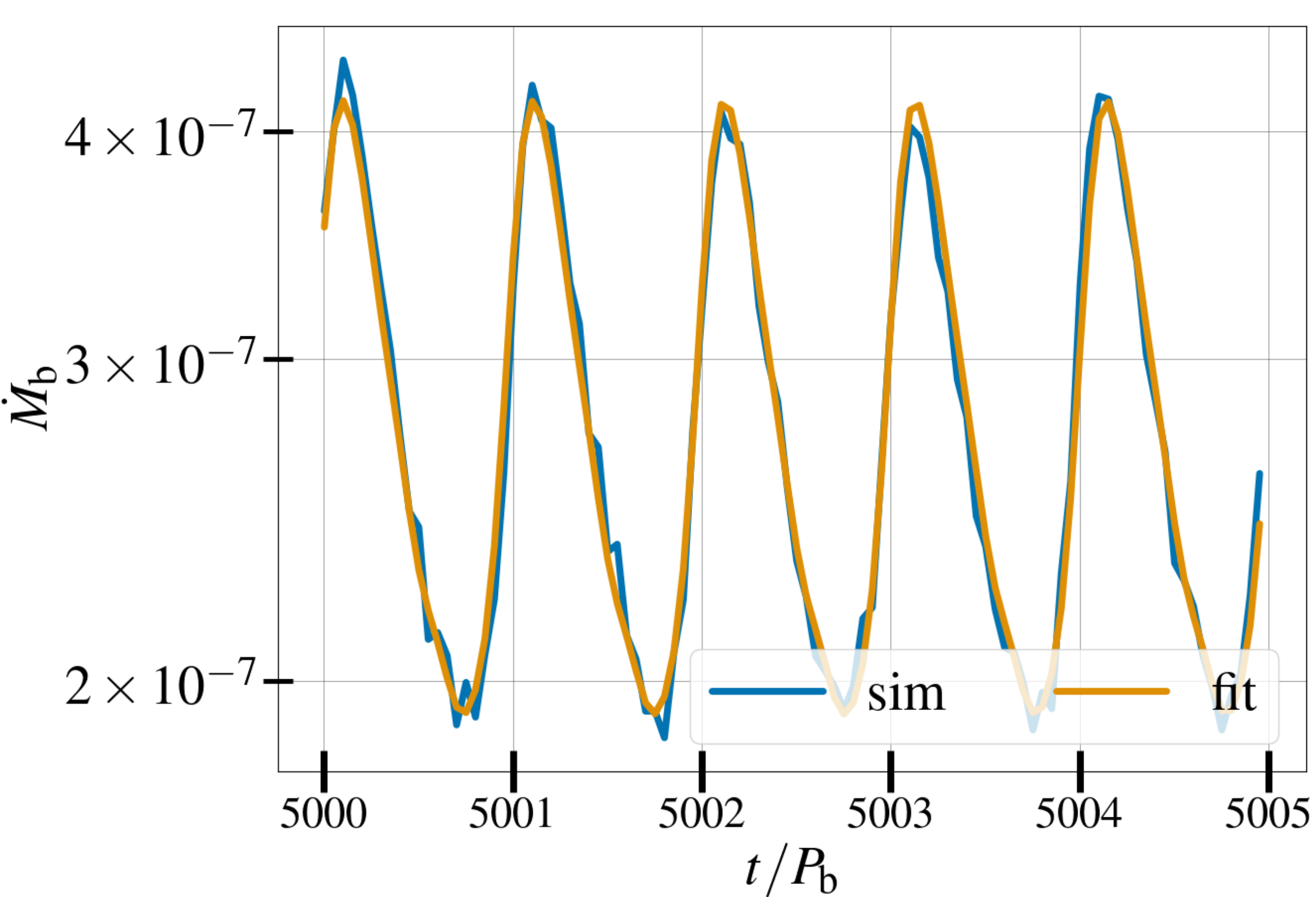


# Signatures of Circumbinary Disk Physics in MBHB Populations

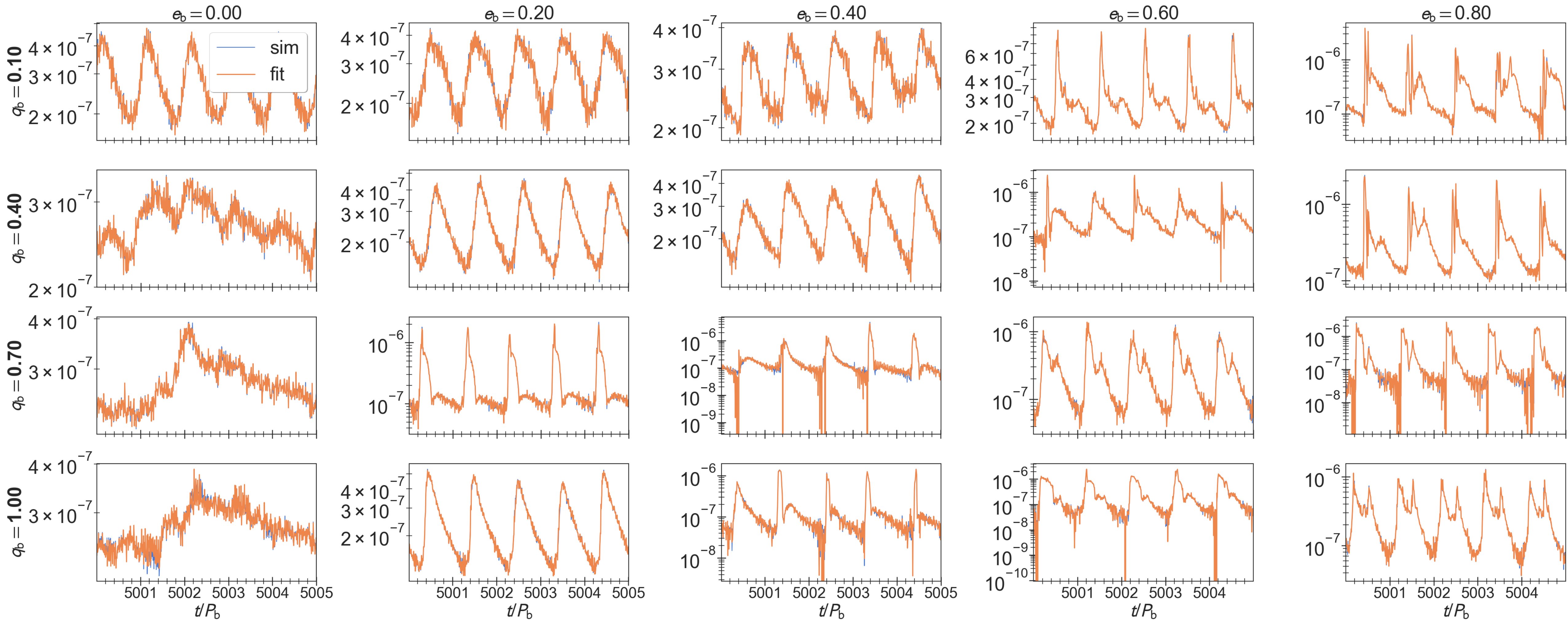
1. MBHBs: Formation & Evolution
2. Circumbinary Disk (CBD) Simulations
3. CBD physics in PTA, LSST (& LISA) Binaries
4. Electromagnetic Signatures & CBD accretion variability



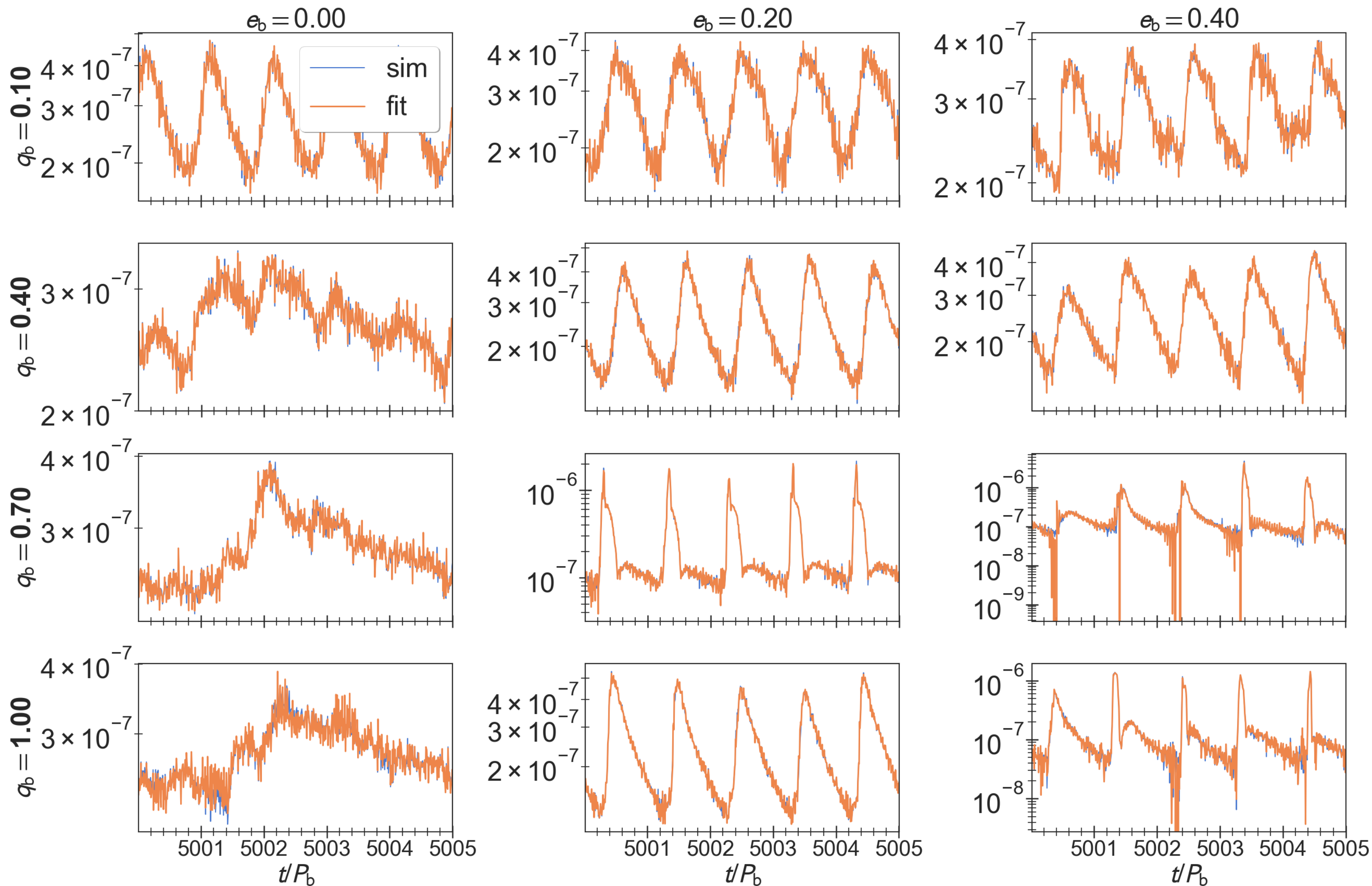
# Multi-messenger signatures from CBD accretion: Variability



# Multi-messenger signatures from CBD accretion: Variability



# Multi-messenger signatures from CBD accretion: Variability



\* Fourier decomposition of accretion variability

\* How much **power** in each **frequency**?

\* Tell-tale signatures pointing to eccentricity, mass ratio?

\* Goal: **map observed variability to eccentricity and mass ratio** to decode MBHB population

# Summary & Conclusions

## 1. CBD physics

dominates  
eccentricity  
evolution

## 2. MBHB populations:

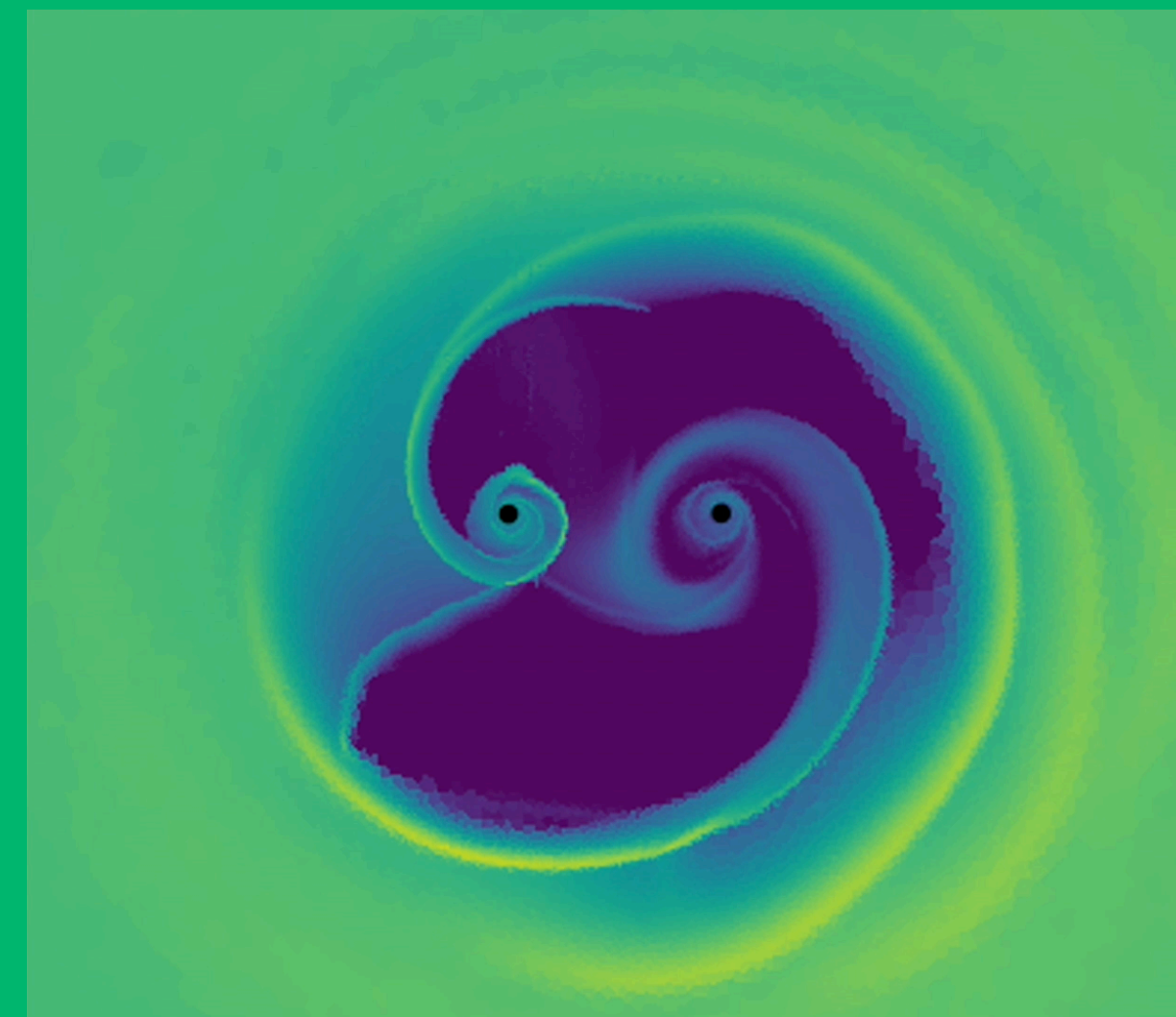
$q_b \gtrsim 0.6$  and  
 $e_b \lesssim 0.5$

## 3. Signature of CBD physics:

**eccentricity vs  
mass ratio**

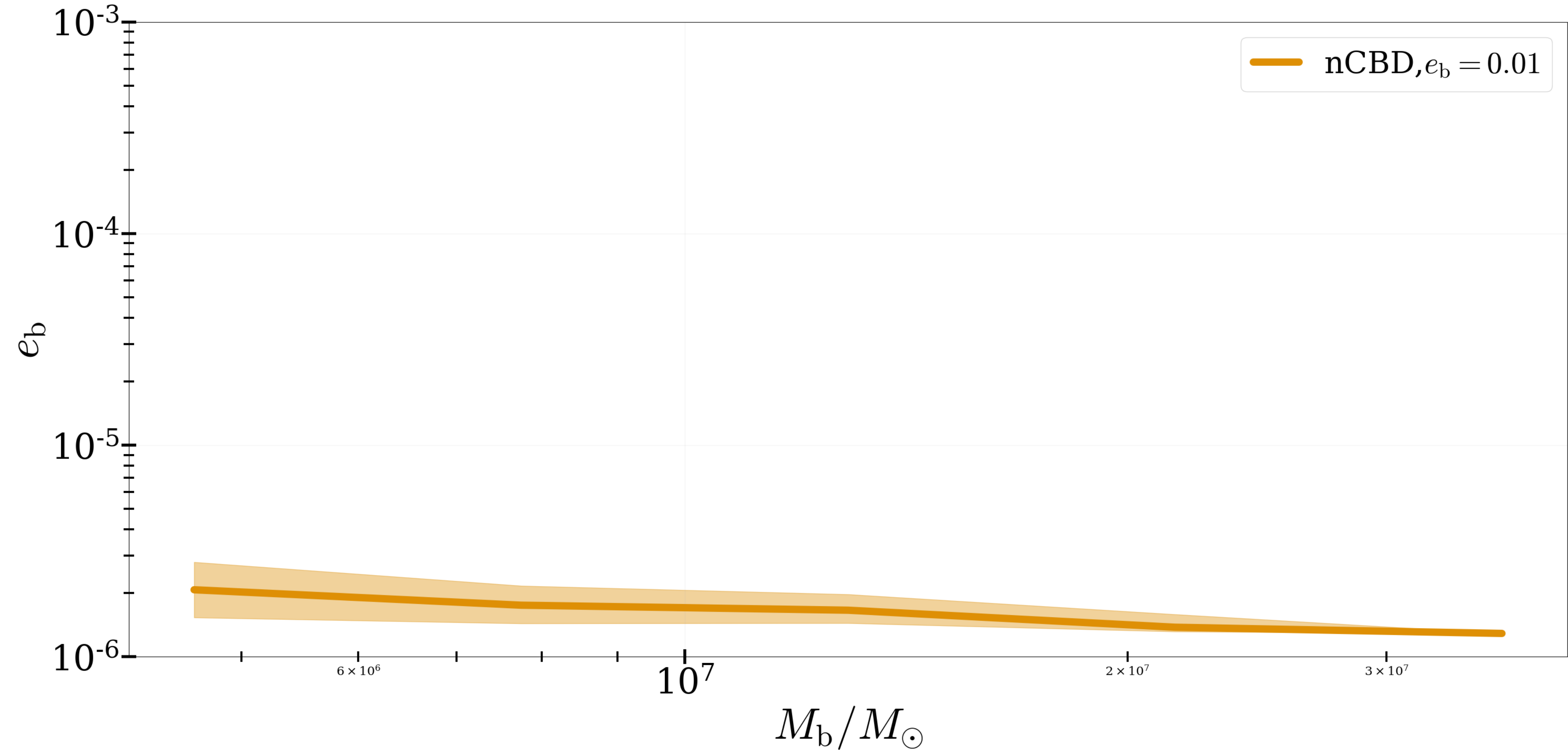
## Future Work:

- **LISA** Population  $M_{\text{BH}} \lesssim 10^6 M_{\odot}$
- Multi-messenger **transients**
  - MBHB **spins**
  - Binary AGN **feedback**

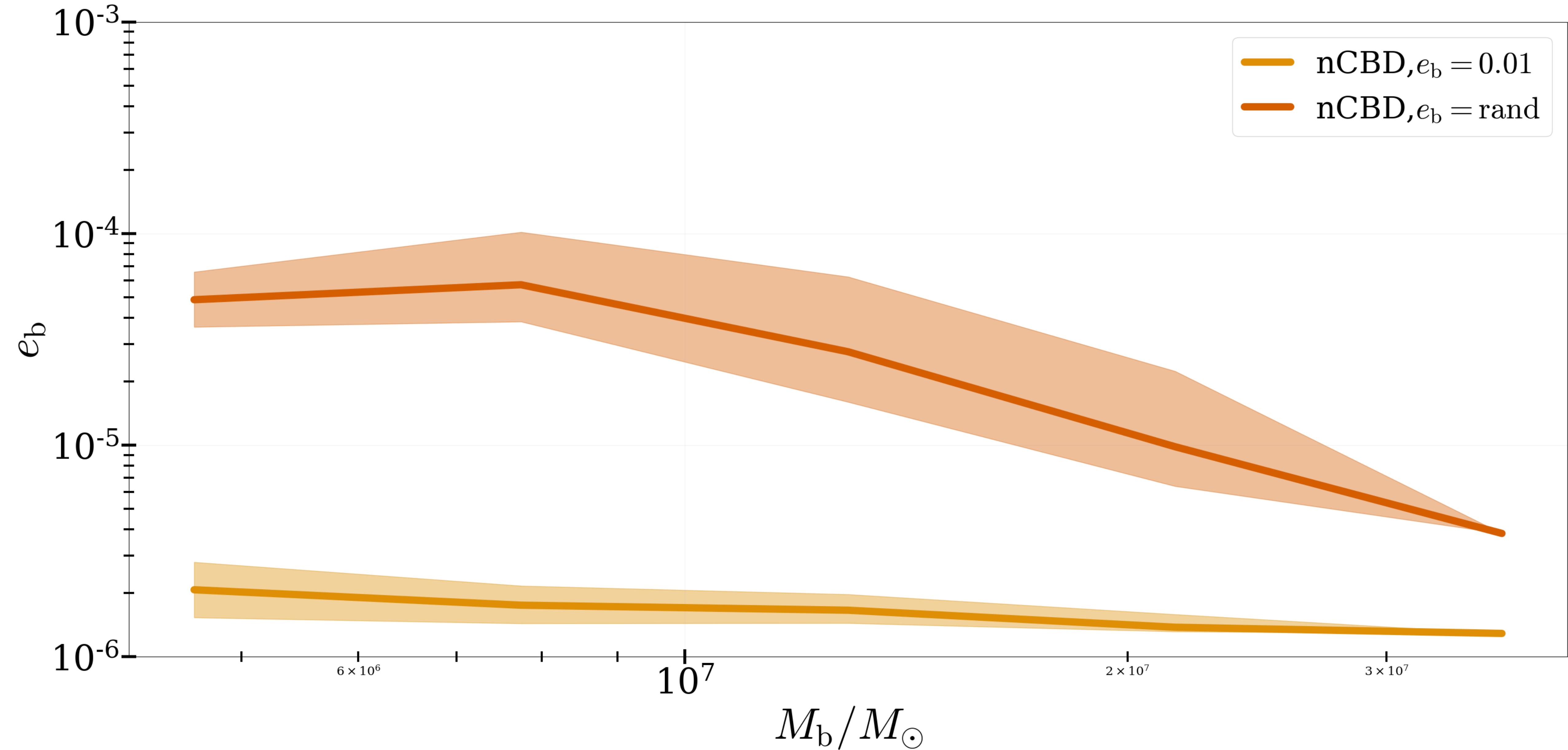


# Additional Slides

# Eccentricity vs Mass in **LISA** binaries

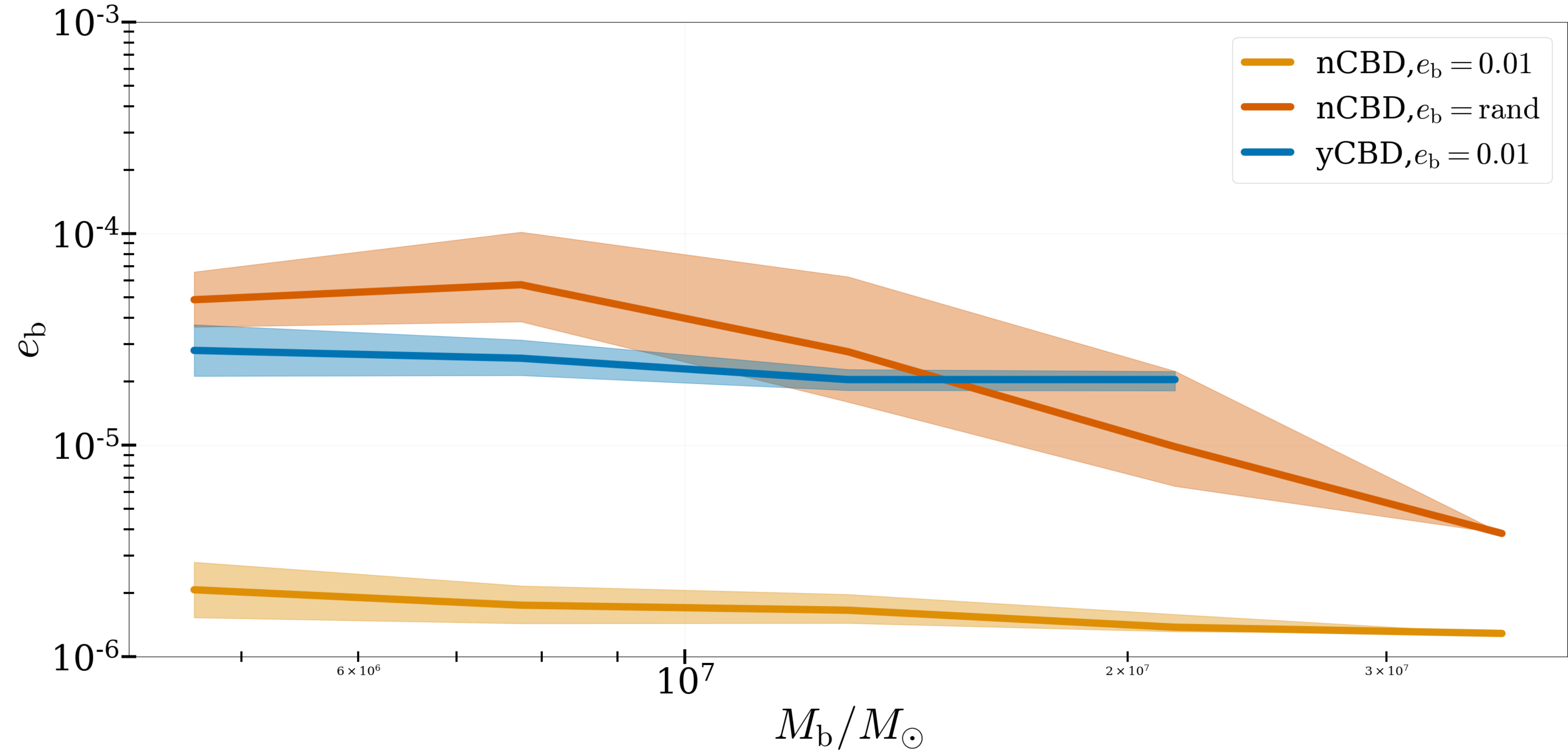


# Eccentricity vs Mass in **LISA** binaries

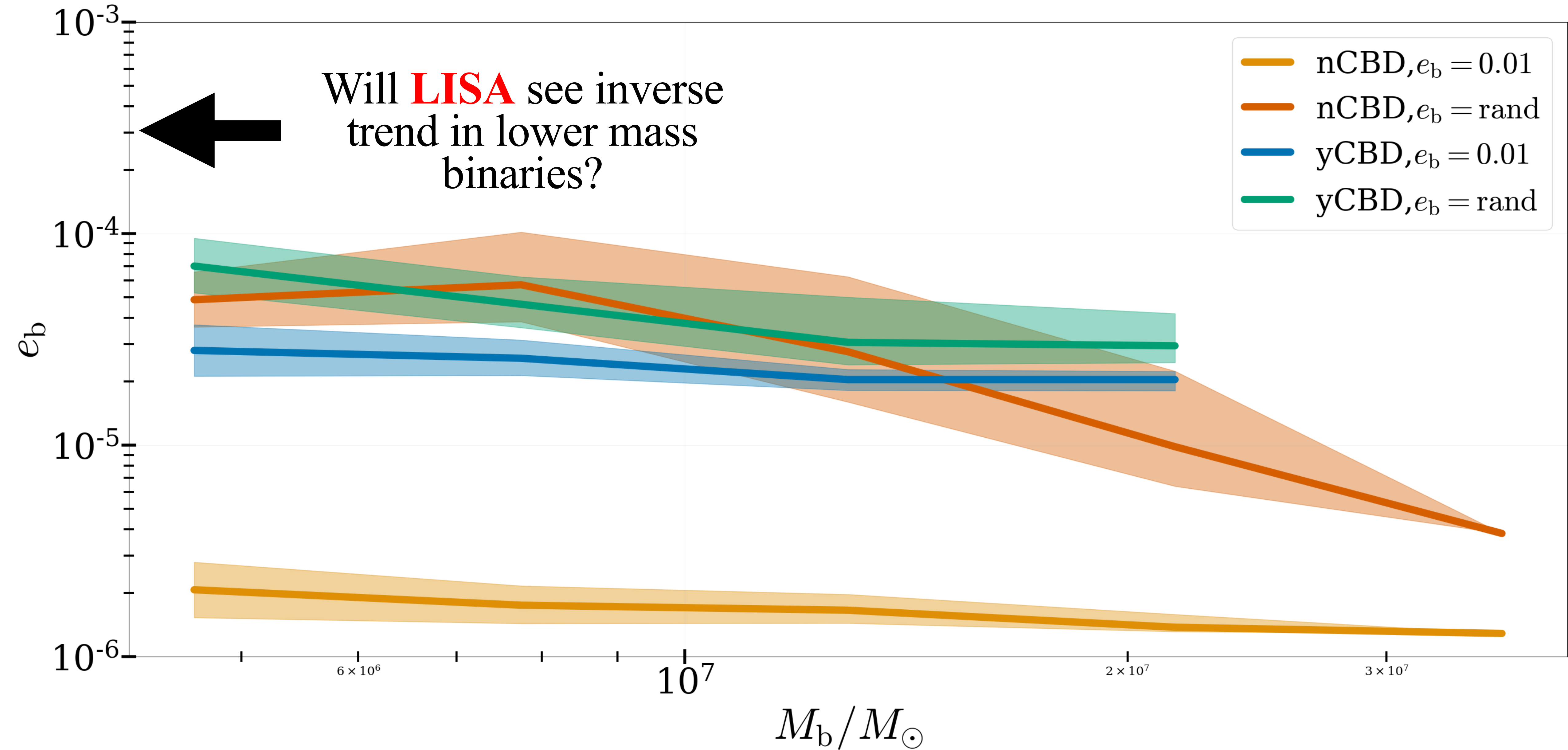




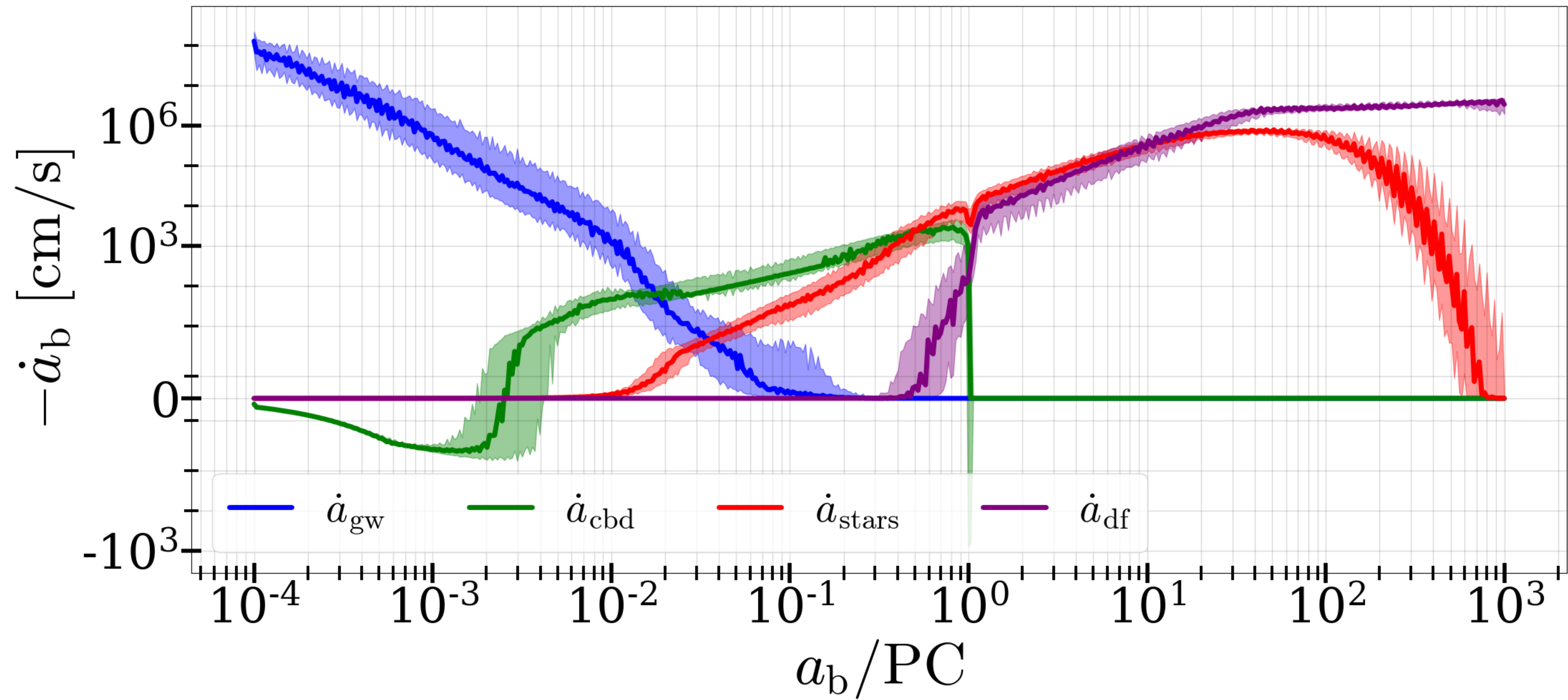
# Eccentricity vs Mass in **LISA** binaries



# Eccentricity vs Mass in **LISA** binaries



# The Evolution of Massive Black Hole Binaries

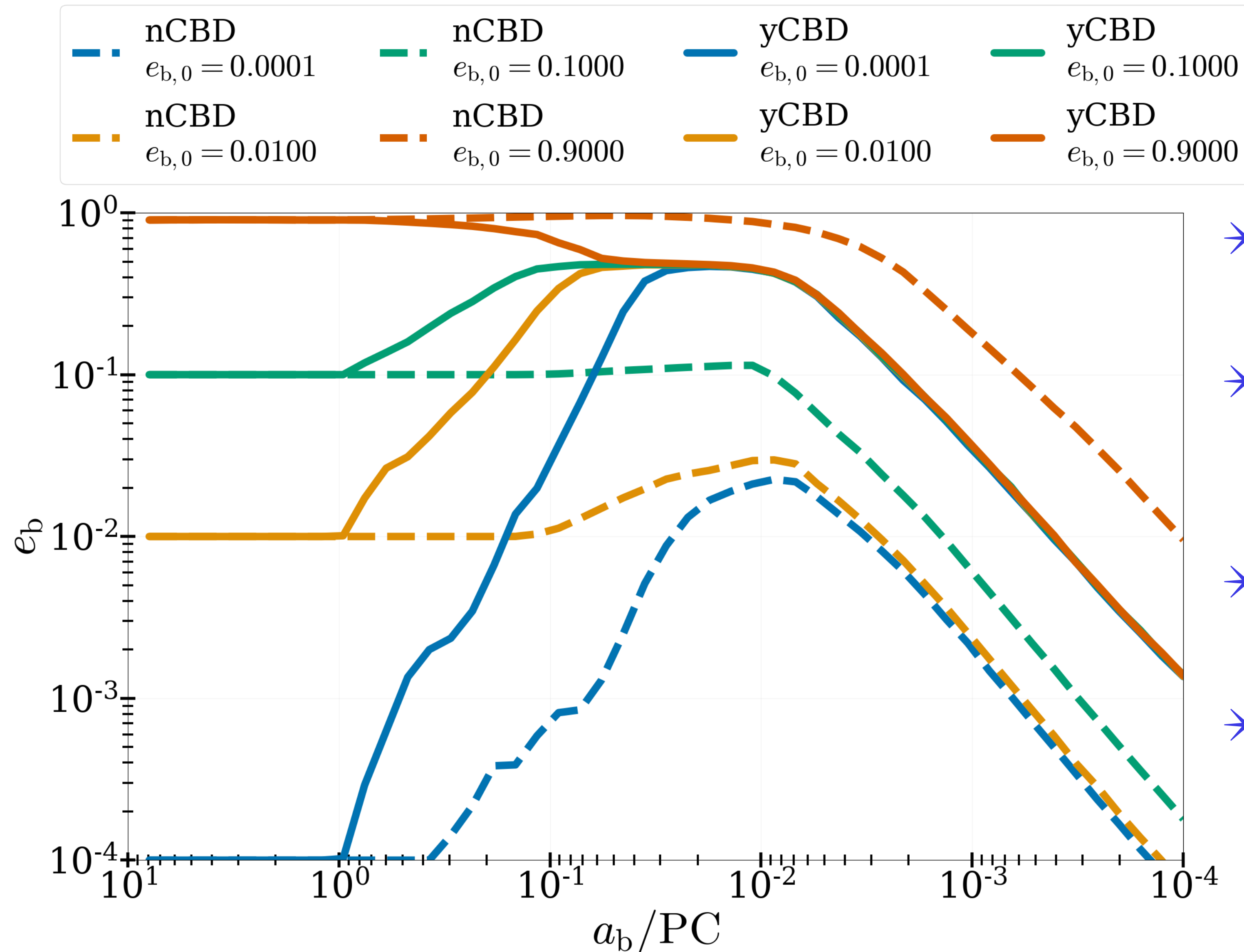


← MBHB evolution

Siwek+24 (in prep)

# Eccentricity evolution of MBHBs across frequency

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



\* Initial eccentricity highly uncertain

\* Depends on **galaxy merger** conditions (e.g. Rawlings+23)

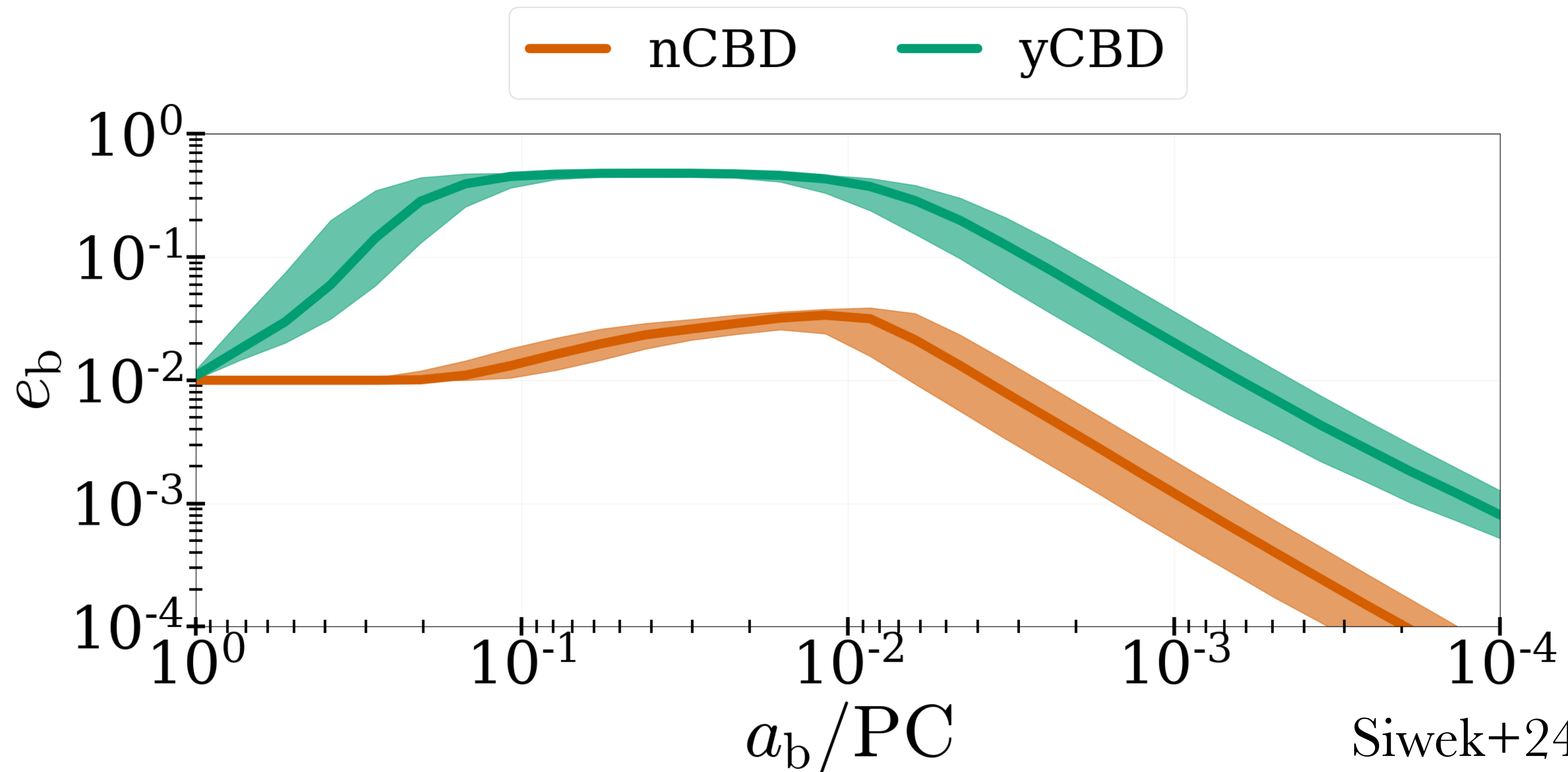
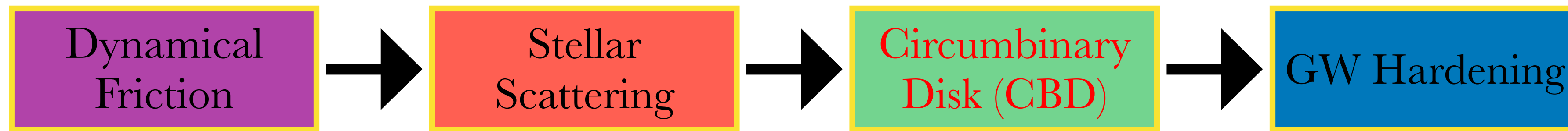
\* CBD **erases** this uncertainty!

\* Eccentricity evolution **independent** of initial state

Siwek+24 (in prep)

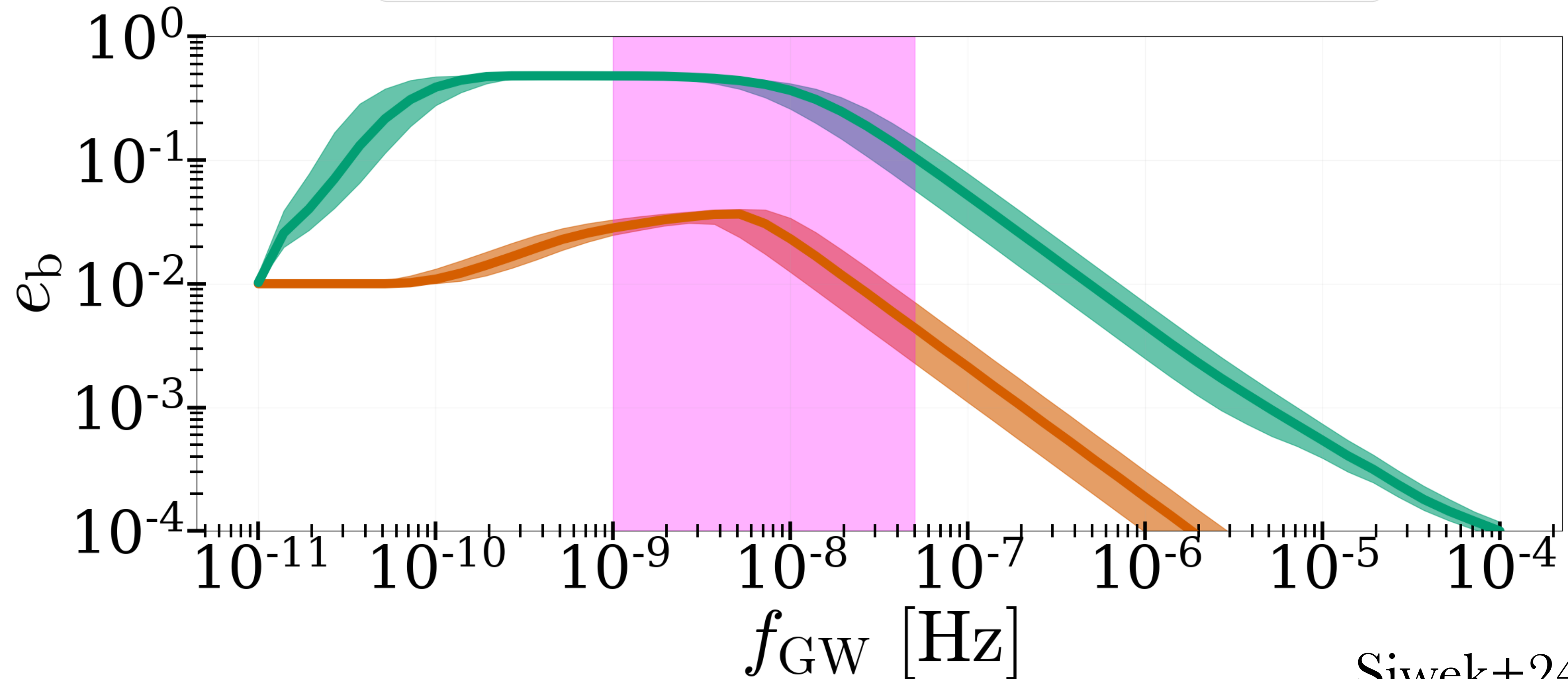
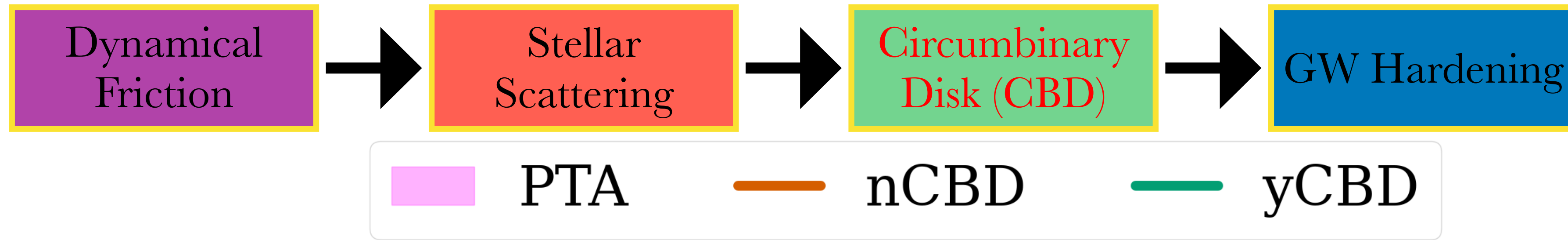
# Eccentricity evolution of MBHBs: final parsec

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



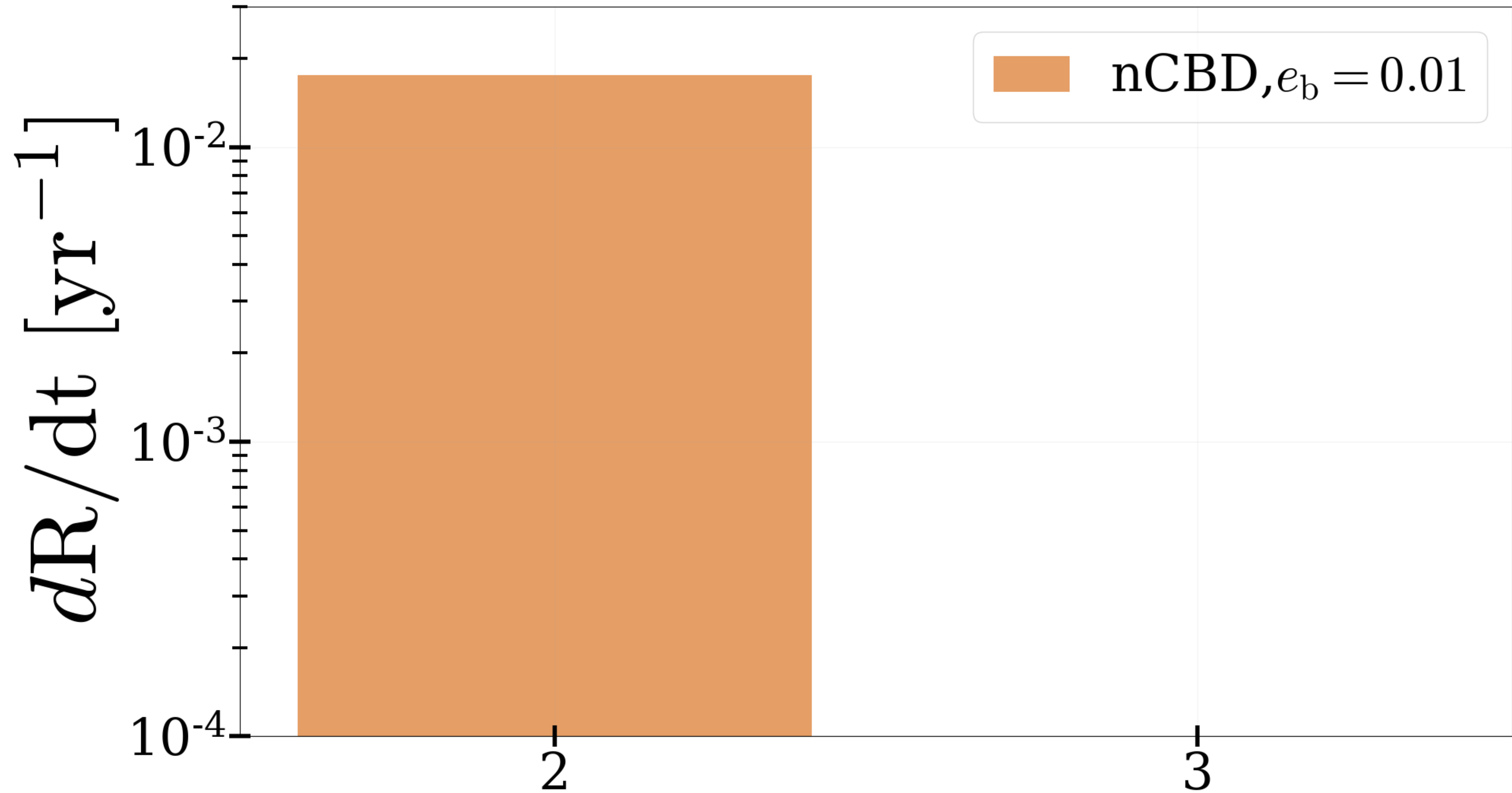
# Eccentricity evolution of MBHBs across frequency

**2749** MBHBs from **Illustris** evolved with NANOGrav's **holodeck** SAM (Kelley+ in prep)



Siwek+24 (in prep)

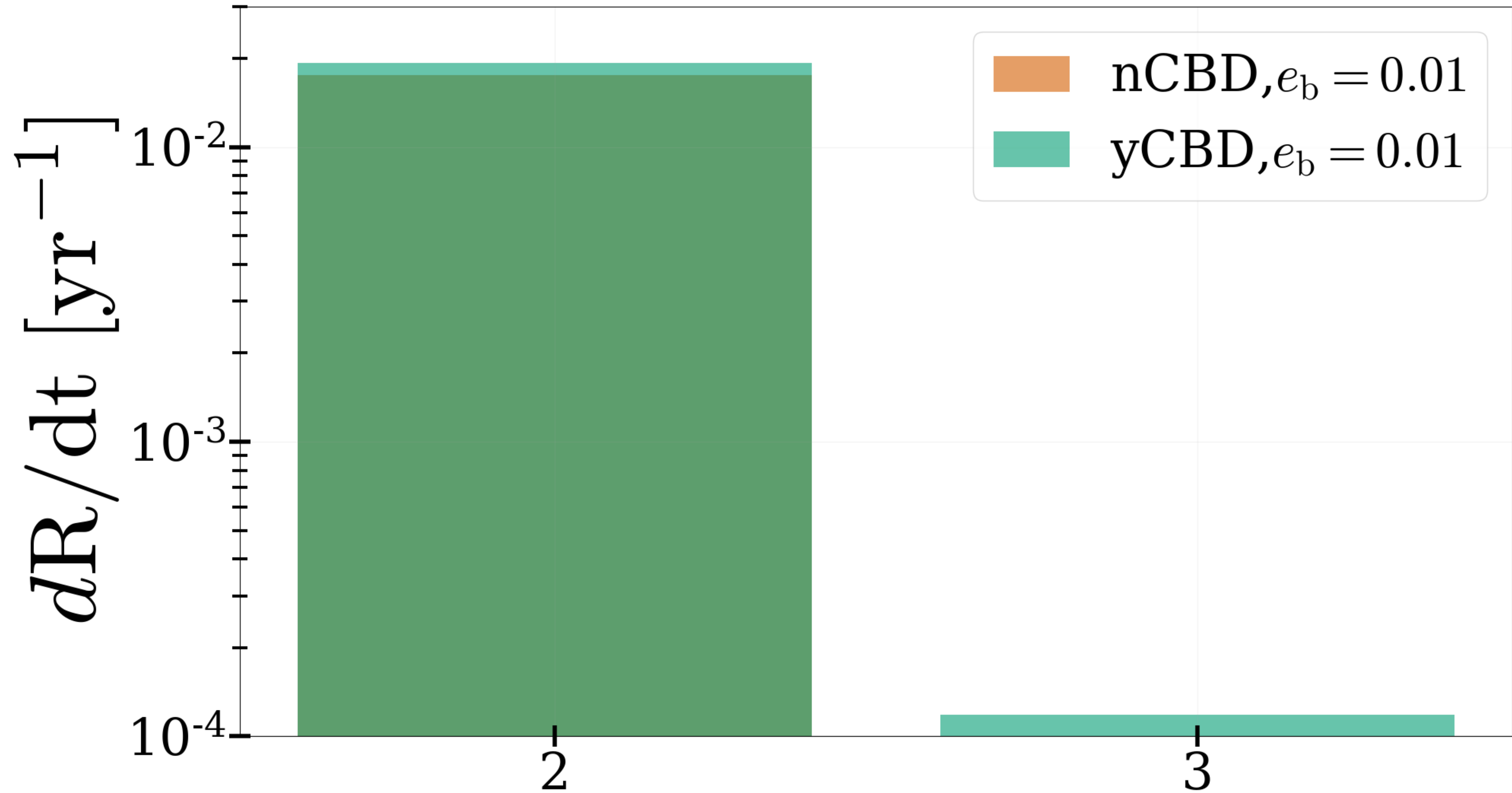
# LISA Detection Rates



$n_{\text{harmonic}}$

Siwek+24 (in prep)

# LISA Detection Rates: 1% Eddington

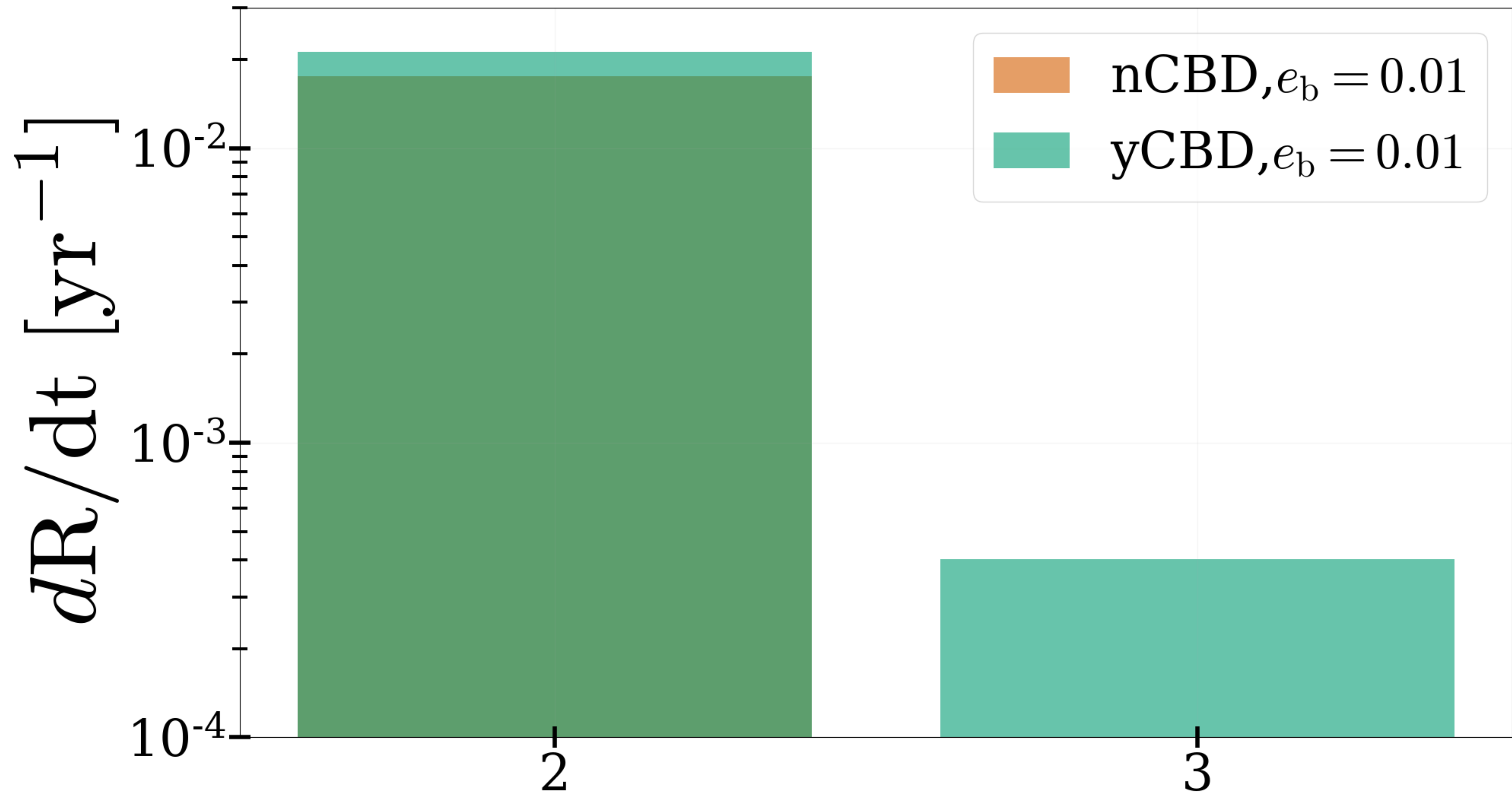


$n_{\text{harmonic}}$

Siwek+24 (in prep)



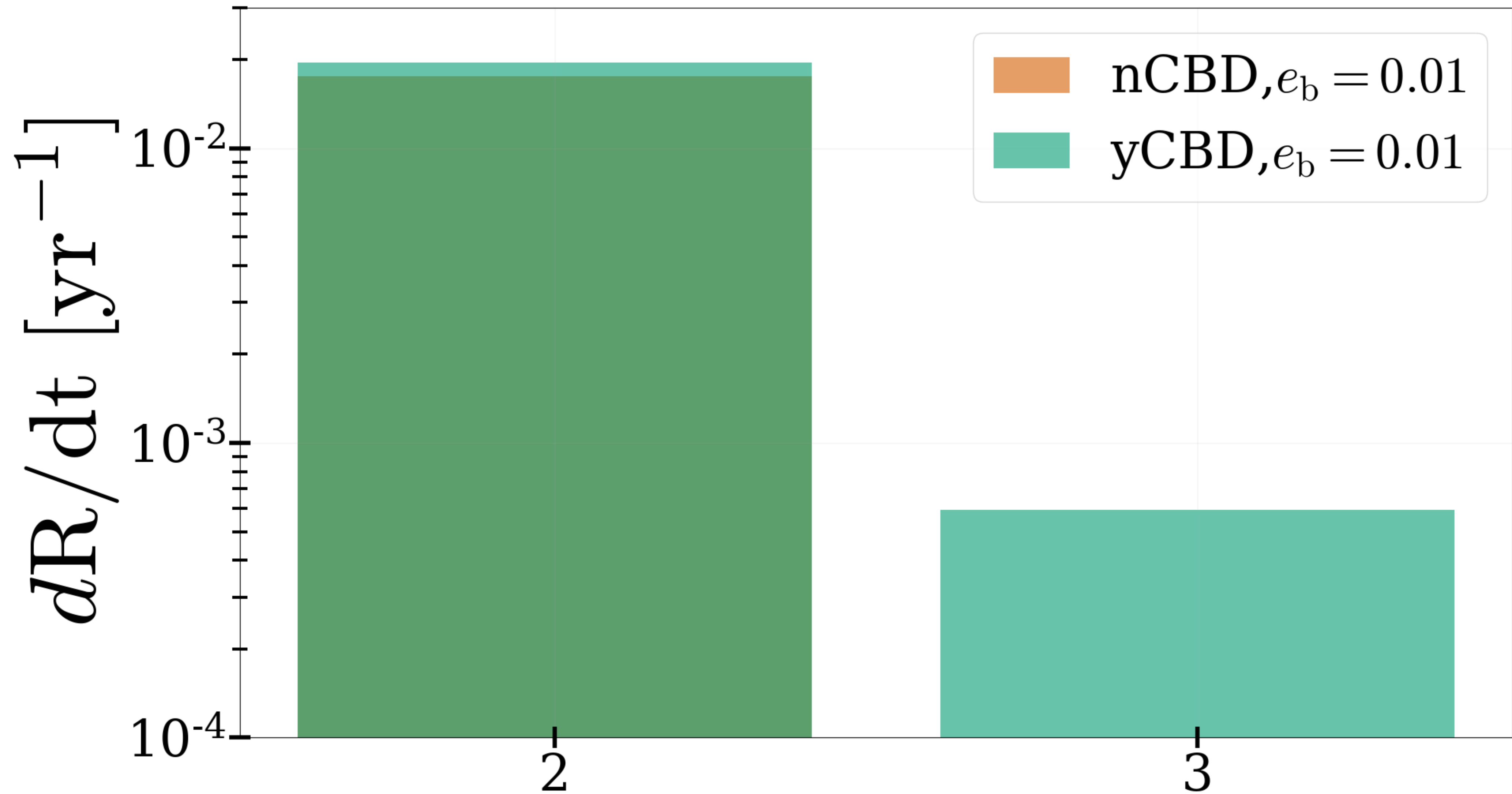
# LISA Detection Rates: 10% Eddington



$n_{\text{harmonic}}$

Siwek+24 (in prep)

# LISA Detection Rates: 100% Eddington



$n_{\text{harmonic}}$

Siwek+24 (in prep)